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Little engagement of attention by salient distractors defined in a different dimension or modality to the visual search target

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Abstract

Singleton distractors may inadvertently capture attention, interfering with the task at hand. The underlying neural mechanisms of how we prevent or handle distractor interference remain elusive. Here, we varied the type of salient distractor introduced in a *visual* search task: the distractor could be defined in the same (shape) dimension as the target, a different (color) dimension, or a different (tactile) modality (intra-dimensional, cross-dimensional, and, respectively, cross-modal distractor, all matched for physical salience); and besides behavioral interference, we measured lateralized electrophysiological indicators of attentional selectivity (the N2pc, Ppc, P_D, CCN/CCP, CDA, and cCDA). The results revealed the intra-dimensional distractor to produce the strongest reaction-time interference, associated with the smallest *target*-elicited N2pc. In contrast, the cross-dimensional and cross-modal distractors did not engender any significant interference, and the *target*-elicited N2pc was comparable to the condition in which the search display contained only the target singleton, thus ruling out early attentional capture. Moreover, the cross-modal distractor elicited a significant early CCN/CCP, but did not influence the *target*-elicited N2pc, suggesting that the tactile distractor is registered by the somatosensory system (rather than being proactively suppressed), without, however, engaging attention. Together, our findings indicate that, in contrast to distractors defined in the same dimension as the target, distractors singled out in a different dimension or modality can be effectively prevented to engage attention, consistent with dimension- or modality-weighting accounts of attentional priority computation.

KEYWORDS

CCN, CCP, dimension-weighting account, distractor suppression, ERP, N2pc, Ppc

1 | INTRODUCTION

While engaged in a task, such as writing a manuscript, it is easy for our flow to be disrupted by a pop-out email alert or a vibrating phone. Controlling attention and handling distractor interference is not only practically important, but also has theoretical significance. Yet, the underlying mechanisms remain controversial (for a review, see

Luck et al., 2021). While preventing attentional capture by salient distractors is beneficial for goal-oriented target selection, the timing and operation of distractor suppression are still a topic of debate. Researchers advocating a bottom-up view posit that salient distractors inevitably capture attention early on Theeuwes (1992, 2010), with distractor suppression coming into play only afterwards through reactive inhibition and attendant disengagement of attention from the distractor. In contrast, researchers emphasizing top-down processes argue that target-irrelevant features and/or dimensions can be proactively suppressed through top-down feature- (Becker et al., 2010; Folk et al., 1992; Leber & Egeth, 2006a), or dimension-based (Liesefeld, Liesefeld, & Müller, 2019; Liesefeld & Müller, 2020; Müller et al., 1995) stimulus set, preventing (or, at least, minimizing) attentional capture by salient distractors in the first instance (Gaspelin et al., 2015). In light of previous studies and, specifically, an explanatory framework developed in our previous work (which we will review next), the present study was designed to examine how efficiently we can handle salient but task-irrelevant distractors defined in a different stimulus modality to the target compared to distractors defined in the same modality, but in a different dimension and distractors defined in the same dimension as the target.

1.1 | Evidence for dimension- and, respectively, modality-based distractor handling

To study distractor-handling mechanisms, a widely used scenario is the "additional-singleton" search task pioneered by Theeuwes (1992, 2010). Typically in this task, participants search for and respond to a target defined by an odd-one-out (i.e., *singleton*) shape (e.g., a square) in an array of shape-homogeneous non-targets (e.g., circles), one of which is a color singleton (e.g., red, whereas the target and the other non-targets are all blue); and the (compound-task) response requires participants to discern the orientation of a small line segment inside the target shape. A ubiquitous finding (since Theeuwes' pioneering studies) has been that the presence (vs. absence) of a competing color singleton in the search array causes reaction-time (RT) interference, that is: it slows the RTs to the target, which has been attributed to the inadvertent capture of attention by the additional color-singleton "distractor." However, a plethora of studies have shown that this interference effect can be reduced if the distractor's defining feature (e.g., red) is fixed (e.g., Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018c; Vatterott & Vecera, 2012), if the prevalence of distractors is high (e.g., Geyer et al., 2008; Müller et al., 2009; Won et al., 2019), or if the distractor occurs at a predictable display location (e.g., Allenmark et al., 2019; Ferrante et al., 2018; Goschy et al., 2014; Sauter et al., 2018; Wang & Theeuwes, 2018; Won et al., 2019; Zhang et al., 2019) – arguing in favor of some form of proactive distractor suppression.

According to one particular account of distractor handling, which we refer to as "dimension-weighting" account, it is important to consider the feature dimensions in which the distractor and the target are singled out to account for modulations of distractor interference. Originally, this account was developed to explain target selection (and its modulation by inter-trial "history") in visual pop-out search (e.g., Found & Müller, 1996; Müller, Reimann, & Krummenacher, 2003). For instance, finding the same pop-out color-defined target (e.g., a red target among green distractors) was faster when it followed a color-defined target compared to an orientation-defined target; of note, while there was some small advantage for an exact (color) feature repetition, a feature change within the same dimension (e.g., from a blue to a red target) was less costly than a change across dimensions (e.g., from a right-tilted to a red target). Also, cueing on particular feature (e.g., red) to be most likely (79%) to be target defining on a given trial led to a search-RT advantage when the target actually defined by this feature (red); however, there was an advantage even when the target was defined by a different feature within the (implicitly) cued dimension (e.g., color: blue; 7% likely), compared to a feature in an (implicitly) uncued dimension (e.g., orientation: right- or left-tilted; each 7% likely). Müller and his colleagues interpreted these predominantly dimension-based inter-trial and cueing effects (as well as cross-dimensional redundancy-gain effects; e.g., Krummenacher et al., 2001, 2002) in terms of a hierarchical architecture where feature-contrast signals registered in the respective feature dimensions are integrated, across dimensions, by units in a search-guiding attentional priority map in a *weighted* fashion, with the integration weight of a given dimension determined by both inter-trial history and top-down set.[1]

[1]While Liesefeld and Müller (2020) have drawn a strong distinction between priority-guided- and feature-template-driven (i.e., in their terms, "clump-scanning") search, in principle the DWA framework would allow for an element of feature-specificity in attentional selection over and above dimension-specificity, as observed by Found and Müller (1996) and Müller, Reimann, and Krummenacher (2003) especially for color-defined targets. For instance, entry-level coding of a particular target feature might be enhanced top-down (by setting up the appropriate template), giving this feature an edge. However, for attention to be allocated to the location of the target, its feature-contrast signal (even though top-down enhanced) would still be dimensionally weighted (with the same weight as for any other feature-contrast signal within the target dimension) at the integration stage: the search-guiding priority map.

In subsequent work, this framework – referred to as "dimension-weighting account" (DWA) of attentional-priority computation – was applied to the handling of salient distractors. The hypothesis was that distractors singled out in another dimension to the target (cross-dimension distractors, e.g., a color distractor when searching for an orientation target) can be "filtered out" relatively efficiently by globally down-weighting any feature-contrast signals emerging in the distractor dimension (while up-weighting signals emerging in the target dimension); however, dimension-based down-weighting does not work when the distractor is defined (by another feature) within the same dimension as the target (intra-dimension distractor), because, in this case, the down-weighting would compromise target detection: one cannot both down-weight and up-weight one-and-the-same dimension (see, e.g., Sauter et al., 2021, for a development of this argument). Accordingly, distractor interference would be greater with intra- as compared to cross-dimension distractors, even when both types of distractor are equated for bottom-up saliency. This prediction was borne out by a number of studies, including studies of statistical learning of distractor handling, using orientation- (or shape-) defined targets and color- (or luminance-) defined distractors (e.g., Goschy et al., 2014; Liesefeld, Liesefeld, & Müller, 2019; Sauter et al., 2018, 2021; Won et al., 2019; Zehetleitner et al., 2012; Zhang et al., 2019, 2022). We attributed the interference reduction by cross-dimensional distractors to the operation of "dimension-based" suppression.[2] Following Gaspelin and Luck (2018a, 2018b), Won et al. (2019) referred to a similar effect pattern (specifically, that participants showed comparable distractor interference when the distractor color was fixed vs. when it selected randomly on a trial from a set of up to 196 colors) as "second-order feature suppression."

An extension of the DWA is the "modality-weighting account" (MWA) proposed by Töllner et al. (2009) to account for performance in (pop-out) search scenarios with targets unpredictably defined in one of several stimulus modalities (e.g., vision and touch), rather than just in one of several dimensions within the same modality (e.g., vision: color and shape). The MWA postulates that, in such scenarios, attentional selection is governed by a multi-modal priority map which integrates the weighted outputs of modality-specific priority maps. While there is evidence for such an additional level in the computation of (multi-modal) attentional priority (e.g., Nasemann et al., 2023), this account too would predict that distractor signals emerging in a non-target modality can be (at least) as effectively suppressed – by modality-based down-weighting – as distractors signals defined within the same modality but a different dimension to the target can be suppressed by dimension-based down-weighting. Thus, according to the DWA/MWA, an intra-dimension distractor should cause stronger interference (indicative of attentional capture) relative to both cross-dimension and cross-modality distractors, because they can be effectively suppressed or down-weighted through dimension- or modality-based weight settings.

Note, though, that the results of a study by Gaspar and McDonald (2014) are seemingly at variance with the notion of dimension-based (and, by extension, "modality-based") distractor suppression. Gaspar and McDonald compared three visual distractor conditions in separate experiments (with different participants). In Experiment 1, both the target and distractor singletons were color-defined and the distractor (red) was more salient (i.e., generated greater feature contrast) than the target (yellowish) relative to the (green) background elements. In Experiment 2, the distractor was defined in a different dimension (color) to the target (shape): the distractor was the same red element as in Experiment 1, while the target was an odd-one-out diamond among circular background elements (which previous research had shown to be less salient than a red color distractor). In Experiment 3, the two singletons were again both color-defined, but this time the target (red) was more salient than the distractor (yellowish). Gaspar and McDonald examined both the pattern of RT distractor-interference effects under these conditions as well as electrophysiological markers indicative of the underlying dynamics, in particular, the so-called (lateralized) distractor positivity component (P_D) of the event-related potential (ERP), which is taken to reflect processes of distractor suppression (see below for further details). Behaviorally, distractor RT interference turned out larger in Experiment 1 than in Experiments 2 and 3.[3] And electrophysiologically, lateral distractors (with the target positioned on the vertical midline) elicited a robust P_D some 250–300 ms post stimulus onset in Experiment 1, a smaller but significant P_D in Experiment 2, and no P_D in Experiment 3.

Taking the P_D to reflect *location-based* distractor suppression, Gaspar and McDonald reasoned that the less salient

[2]There is a debate regarding the term "distractor suppression": while some authors advocate confining the use of this term to situations in which a distractor (location) is "suppressed" *below* the distractor-absent baseline, most researchers use a laxer definition, namely, in terms of a "down-modulation" of the potential of a distractor to capture attention by pushing its activity toward the baseline (e.g., Ipata et al., 2006). According to the DWA, what is down-modulated is the multiplicative weight (>0) assigned to saliency, or "feature-contrast", signals that arise in the distractor dimension, in the computation of the overall (i.e., supra-dimensional) attentional-priority map. Accordingly, we use "suppression" here in terms of "down-weighting."

[3]Overall RT interference was significant even in Experiment 3, and not significantly reduced compared to Experiment 2. The fact that even a distractor less salient than the target can cause interference is consistent with the stochastic "distractor-capture" model explicated by Zehetleitner et al. (2013).

color distractor in Experiment 3 would not elicit a P_D because there is little need for suppression to select the equally salient color target. And, to explain the reduced P_D elicited by the same (red) color-defined distractor in Experiment 2 versus Experiment 1, they conjectured that the target-defining dimension (shape) was selectively up-weighted in Experiment 2, reducing the saliency difference of the distractor relative to the target and thus the need to apply suppression to prevent attentional capture. In contrast, selective up-weighting of the target dimension was not possible in Experiment 1, as both singletons were defined in the same dimension (color) – resulting in a greater need to operate suppression. Gaspar and McDonald (2014) preferred this (location-based) account to that of *dimension-based* distractor suppression, which – they argued – could not coherently explain the pattern of P_D effects. In particular, if the latter account attributes the P_D observed in Experiment 2 to dimension-based distractor suppression, it "[cannot] provide a plausible account of the [larger] P_D observed in Experiment 1 due to the within-dimension competition conditions" (p. 5663), under which dimension-based suppression is not applicable by definition.

However, in our own electrophysiological work, we never considered the (relatively late) P_D to reflect dimension-based suppression (which we conceive of as a *proactive* global "filtering" process), but instead to index *reactive* local suppression in case some proactive distractor-shielding mechanisms (such as, if applicable, the dimensional "filter" set) failed to prevent attentional capture (see, e.g., Liesefeld et al., 2017; 2019). Given that dimension-based suppression is applicable only when the distractor is defined in a different dimension to the target, the same (physically salient) task-irrelevant singleton is more likely to capture attention when it is an intra- rather than a cross-dimension distractor (e.g., Gaspar & McDonald, 2014; Liesefeld et al., 2019; see Sauter et al., 2021, for evidence from oculomotor capture). Accordingly, there is a greater need for reactive suppression in the intra-dimension condition, reflected in the larger P_D. This is very similar to the account preferred by Gaspar and McDonald (2014), except that they assume that the reduced P_D in their cross-dimension condition is owing to up-weighting of the target dimension – rather than down-weighting of the distractor dimension.[4]

Computationally (in terms of RT modeling), it is hard to distinguish up-weighting of the target dimension from down-weighting of the distractor dimension (see, e.g., Liesefeld & Müller, 2021, Appendix S4). In fact, to account for dimension-based inter-trial effects, Müller and colleagues (e.g., Found & Müller, 1996; Krummenacher et al., 2001, 2002; Müller, Reimann, & Krummenacher, 2003) proposed an automatic weight linkage between (currently) relevant and irrelevant dimensions, so that increasing the weight of one dimension is associated with a decrease of the weights for other dimensions (akin to the idea of weight normalization, as assumed for instance in theories such a TVA; Bundesen, 1990).[5] Experimentally, however, it is possible to render selective up-weighting of the target dimension in the cross-dimension distractor condition unlikely if the target is consistently defined in one (fixed) dimension while cross- and intra-dimension distractors are occurring randomly intermixed across trials (rather than being presented in separate blocks or experiments, as in the study of Gaspar & McDonald, 2014). In this case, one can assume that the same weighting is applied consistently across trials to the target dimension (while non-target dimensions, and perhaps modalities, are down-weighted). Given this, any differential interference (and underlying electrophysiological) effects between cross- and intra-dimension distractors would be attributable to differential handling of the two types of distractor (consistent with the DWA), rather than shifts in the "target" baseline. For this reason, we randomized the type of distractor in the present study.

In addition to intra- and cross-dimension distractors, we also introduced a cross-modality distractor (as a third distractor type) to test the MWA. Evidence on the handling of such distractors is scarce. In fact, we know of only one recent study, by Mandal and Liesefeld (2022), see also Mandal et al. (2022), who examined the effects of cross-modality, *auditory* distractors on visual search. Based on four experiments, they concluded that "task-irrelevant auditory stimuli have no impact on the performance of a visual pop-out search" (p. 3887). While this would be consistent with the MWA, Mandal and Liesefeld did not compare the effects of cross-modal (auditory) and cross-dimension visual (color) distractors within the same experiment, and they did not test an intra-dimension visual (orientation) distractor. Accordingly, we are not aware of any test of the full interference pattern predicted by the DWA/MWA.

[4]We acknowledge that, here, we gloss over intricacies in Gaspar & McDonald's (2014) electrophysiological data that might not readily square with our account. However, at least with the intra-dimensional search scenario employed by (Liesefeld et al., 2017), we found a clear effect sequence with the (more salient) intra-dimension distractor first generating an N2pc, which was followed by (what we considered an *active*) P_D, with the N2pc referenced to the (lass salient) target being delayed in the presence of a distractor. In a recent follow-on study that also included cross-dimension distractors, distractors produced a strong P_D, but no N2pc and no significant delay in the target-referenced N2pc (Liesefeld et al., 2022).

[5]Whether this fully captures the competitive weighting dynamics or whether the weights may also be modulated independently for a target- and, respectively, a distractor-defining dimension (at least to some degree) remains an open issue.

Given this, the present study was designed to examine the above, core prediction deriving from the DWA/MWA by comparing the pattern of interference effects between visual intra-dimension (shape-defined), visual cross-dimension (color-defined), and tactile cross-modality distractors in visual search for a shape-defined target. In addition to examining the pattern of RT interference, in our critical Experiment 1, we also recorded the electroencephalogram (EEG) during task performance and examined a number of lateralized event-related potentials (or event-related lateralizations, ERLs) that have been interpreted as brain signatures of attentional selection (including distractor "capture" and suppression) in visual and tactile search, in particular: the posterior-contralateral N2 (N2pc), the central contralateral negativity and positivity (CCN and CCP), the distractor positivity (P_D), the target positivity posterior-contralateral (Ppc), and the (central, c) contralateral delay activity (CDA/cCDA). – Before briefly reviewing these ERLs and summarizing our hypotheses of how these components would turn out assuming dimension- and modality-based distractor suppression, it is useful to take a look at our stimulus and task design, which constrains the ERL analyses we can perform to test our hypotheses.

1.2 | Stimulus and task design

The basic setup of *collocated* visual and tactile stimuli is illustrated in Figure 1. Of note, this setup was adopted from Töllner et al. (2009), who had devised it to examine for the processing of pop-out *targets* whose defining features varied randomly (across trials) between the modalities of vision (color) and touch (vibro-tactile frequency). In the present study, we used an updated version of that setup (extended to 10 locations) to examine the interference effects of salient distractors defined by either shape (intra-dimension distractor) or color (cross-dimension distractor) or by vibro-tactile frequency (cross-modality distractor) in search for a visual, shape-defined target; in pilot experiments, we ensured that the three types of distractor were of comparable bottom-up saliency (for further details, see Method section and Appendix S1).

Given that we introduced collocated visuo-tactile stimuli, our display arrays had to be arranged semi-linearly to place the stimulated fingers next to the visual items; this necessarily meant that the targets and distractors appeared at varying distances from the central fixation marker. In this respect, our setup differs from the circular arrays (with fixed center-to-target and distractor distances) most commonly used in the extant literature (e.g., Theeuwes, 1992). However, given that we balanced the target and distractor eccentricities across trials, any "eccentricity" effects should not systematically influence our results. Of note, however, our semi-linear search arrays made it impossible to examine for lateralized target- or distractor-referenced effects with a distractor or, respectively, target placed on the vertical midline (as is common in the relevant EEG literature; e.g., Dodwell et al., 2021; Hickey et al., 2009). Further, given the many relative placements of the target and distractor that were possible in principle in our semi-linear arrays (placement of the two stimuli at different eccentricities on either the same or on opposite sides), we limited these to arrangements with a target and distractor on opposite sides, to make the experiment manageable in terms of the number of trials required for EEG analysis. Finally, instead of the most common compound-search task used in the extant literature (on which a target is

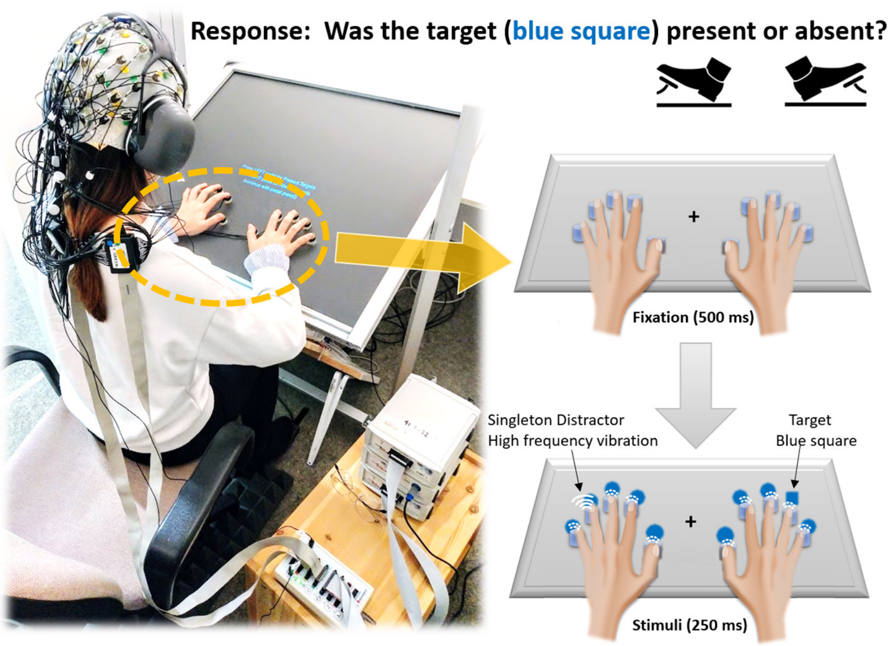

FIGURE 1 Schematic illustration of the experimental setup. Participants sat on a chair, with their fingers placed on tactile (solenoid) vibrators, watching the visual search array that consists of 10 items projected near the tips of their fingers and sensing the solenoid-generated vibrations below their fingertips. The task was to search a blue square among nine distractor items, and to report its presence or absence by stepping on the corresponding foot pedal. Each trial started with the presentation of a central fixation cross for 500 ms, followed by the search display (including the tactile stimuli) presented for 250 ms.

present on every trial), we opted to use a "target-detection" task, which required the introduction of target-absent trials in addition to target-present trials. "Target-present/absent" responses have the advantage of being simpler, in terms of post-selective stimulus-analysis requirements, compared to compound-search tasks (which require a separable target feature from the search-critical feature to be extracted and translated into the appropriate response); and detection tasks permit examining the ERLs that are elicited when a lateralized target is presented in isolation (in the absence of a competing distractor) and, respectively, when a lateralized distractor is presented in isolation (in the absence of a target, on target-absent trials). This differs from the (hitherto) more standard (compound-task) task design (with circular arrays) in which the target- and, respectively, distractor-referenced components are examined under conditions of stimulus competition; that is, even when the distractor appears on the vertical midline and the target lateralized, the distractor competes with the target, potentially impacting the electrophysiological response.

1.3 | Electrophysiology of distractor handling and hypotheses

ERLs are the "difference waveforms" between, typically, posterior EEG activity contra- and ipsilateral to the location of the item of interest. The N2pc component is thought to be a critical neural signature of the lateralized allocation of *visuo-spatial* attention (e.g., Eimer, 1996; Luck, 2011; Luck & Hillyard, 1994; Sawaki & Luck, 2010, 2014; Woodman & Luck, 1999, 2003): it is characterized by greater negativity contralateral to the attended stimulus (e.g., the target) compared to ipsilateral activity around 150–350 ms post stimulus onset. While being regarded, by most researchers, as an indicator of spatial attention shifts, Zivony et al. (2018) have recently argued that the N2pc may instead reflect "processes that occur downstream from attentional shifting", specifically: "... attentional engagement, that is, spatially-specific transient attentional enhancement that promotes feature identification, binding and consolidation of the attended stimulus into working memory" (p. 160). In other words, the amplitude of the N2pc would scale with the attentional processing resources allocated to, or engaged by, a particular stimulus.[6]

[6]This tallies with Zivony and Lamy's (2016, 2018) proposal that there is a qualitative difference between stimulus-driven and goal-driven attentional capture, with stimulus-driven capture involving the summoning of attention but not necessarily its engagement, while goal-driven capture involves both capture and engagement of attention. This idea is similar to Theeuwes's (2010) "rapid-attentional-disengagement" account, which proposes that while irrelevant distractors may capture attention initially, they can be quickly disengaged from.

Thus, if – as hypothesized – an intra-dimension distractor engages attention, it would interfere by reducing the resources available for processing the target, which would be expressed in a reduction of the target-referenced N2pc amplitude in the presence of such a distractor. In contrast, if a cross-dimension or cross-modality distractor can be effectively suppressed (e.g., by rapidly acting, proactive processes), it would not engage attention; accordingly, the target-referenced N2pc should be undiminished in the presence of such a distractor. Also, cross-dimension or cross-modality distractors should not elicit an (or, at most, elicit a reduced) N2pc on distractor-only trials – in contrast to intra-dimension distractors, which cause interference. In addition, given our visuo-tactile stimulus setup, we also examined the CCN (or N140cc): a lateralized negative deflection emerging around 140–340 ms post stimulus over central regions, which is thought to be related to *tactile* attention (Eimer et al., 2004; Eimer & Driver, 2000; Forster et al., 2016; Töllner et al., 2009). Thus, for our vibro-tactile (cross-modality) distractor, we expected that if it initially attracts attention without engaging it further, it should elicit a CCN, but not impact the *visual*-target-referenced N2pc.

Early contralateral positivities preceding the N2pc, such as the posterior contralateral positivity (Ppc) occurring in the 100–200-ms time window (e.g., Jannati et al., 2013; Leblanc et al., 2008), have also been observed in visual search studies. As the Ppc can be elicited by both target and non-target singletons, it has been taken to indicate an early, low-level sensory asymmetry (Luck & Hillyard, 1994) or, respectively, an "attend-to-me" signal (e.g., Jannati et al., 2013; McDonald et al., 2023; Sawaki & Luck, 2010; Stilwell et al., 2022). Another important ERL, proposed to be related to (visual) distractor suppression, is the (already mentioned) P_D component: a positive deflection at electrodes over posterior cortex contralateral to an item that is (to-be) ignored (e.g., Sawaki & Luck, 2010; Stilwell et al., 2022). Depending on when it occurs, distractor suppression would have a significant impact on the amplitude of the target-elicited N2pc. Salient distractor singletons may elicit both a P_D and an N2pc, and in many cases, the N2pc has been reported to be followed by a P_D component, which may reflect a "reactive" process of suppression invoked after attentional capture (e.g., Feldmann-Wüstefeld et al., 2015; Feldmann-Wüstefeld & Schubö, 2013; Gaspar & McDonald, 2014; Hilimire & Corballis, 2014). Assuming that the dimensional weights are set "tonically" (operating even in the absence of, i.e., prior to, stimulus presentation; see, e.g., Schledde et al., 2017), there may be no P_D at all for cross-dimension and cross-modality distractors (because they are filtered passively, rather than actively). Given the hierarchical architecture of attentional-priority computation envisaged by the DWA/MWA, cross-dimension and cross-modality distractors may nevertheless engender a Ppc, that is, an early "attend-to-me" signal (e.g., Eimer, 1996; Jannati et al., 2013; Luck, 2011; Luck & Hillyard, 1994; McDonald et al., 2023; Sawaki & Luck, 2010, 2014; Woodman & Luck, 1999, 2003) – which is then, however, filtered out by dimension- or modality-based down-weighting (see also Footnote 2).

Following the N2pc (and potentially a P_D), the late CDA component (typically in the 400–800-ms time window) is thought to reflect the processing of attentionally selected stimuli in visual working memory (vWM) (Chen et al., 2022; Mazza et al., 2007; Töllner et al., 2013; Vogel & Machizawa, 2004; Woodman & Vogel, 2008). Related to distractor suppression, its amplitude may reflect the processing resources available to decide whether any item represented in vWM is the searched-for target, rather than a task-irrelevant distractor, and then, accordingly, inform the response decision (in our task design: "target-present" vs. "-absent"). By including both distractor-only and target-only trials along with trials on which both a target and a distractor are present on opposite sides (see task design above), we can examine the ensuing CDA for late, post-selective processing of the information represented in vWM. Specifically, we predict that in the target-only condition, the target will be fully represented in vWM, resulting in a significant target-elicited CDA. However, when there is an additional intra-dimension distractor in the display, the target may be selected for vWM along with the distractor (involving the concurrent "sharing" of processing resources) or either only the target or only the distractor is selected, whichever item wins the competition for selection on a trial; both possibilities would be expressed in a diminished target-referenced CDA, compared to the CDA elicited by the target on target-only trials. In contrast, if a cross-dimension or cross-modality distractor, as hypothesized, can be effectively prevented from being selected, it should not be represented in vWM and so not impact the target-referenced CDA. Additionally, effective suppression of a particular distractor type might also be evident in the distractor-referenced CDA on distractor-only trials.

To provide a brief preview, both the behavioral and the electrophysiological results of Experiment 1 turned out as predicted, in particular: while intra-dimension distractors caused significant RT interference, behavioral performance was little impacted by cross-dimension and cross-modality distractors (despite the three distractor types being equated for bottom-up saliency). The ERL analyses indicated that the two latter distractor types, but not the former, could be effectively "decoupled" from attentional selection and kept out of post-selective processing in vWM.

However, even though in line with the predictions from the DWA/MWA, the results of Experiment 1 might be open to alternative interpretations, in particular: "search-mode" accounts of distractor interference (cf. Bacon & Egeth, 1994). The DWA/MWA assume that search performance is based on a standard "saliency-integration" architecture of (visual) search as specified in framework theories such as Guided Search (e.g., Wolfe, 2021): selection is driven by an attentional-priority map, and which stimuli achieve the highest activation at this stage is determined by feature- and dimension- (as well as modality-) based biasing processes. In this regard, the DWA is just a specification of the priority-computation processes in Guided Search. How "search-mode" accounts fit in this framework architecture is less clear (and not our task to specify), but essentially they assume that search may operate, or be forced to operate, in either a "feature-search" mode – in which at least cross-dimension distractors do not interfere (or any kind of distractor that is featurally distinct from the search-critical target features); or search may operate in a "singleton-detection" mode (which would more closely resemble priority-driven search along the lines of GS), in which case all kinds of distractor can cause interference. To address an alternative account of our findings in Experiment 1 in terms of this dichotomy, we conducted two additional, purely behavioral experiments (Experiments 2a and 2b), which manipulated potentially critical aspects of our original design that may have pushed our participants to adopt a particular search mode (in particular, "feature search"). The results indicated that our original findings (in Experiment 1) are not readily accountable in terms of "feature search."

2 | EXPERIMENT 1

2.1 | Method

2.1.1 | Participants

In total, 21 healthy participants, right-handed, (self-reported) normal color and somatosensory perception, none suffering from any neurological or psychiatric disorders, took part in Experiment 1 (10 women; mean age of 26.6, range 20 to 36 years). They signed informed consent prior to the experiment and were compensated for their service at a rate of 9 Euro per hour. The sample size was estimated using G*Power software (Faul et al., 2007), based on previous studies of cross-modal attentional control (Chen et al., 2022; Nasemann et al., 2023) with relatively medium-to-large effect sizes (*f*: 0.3, alpha: 0.05, power: 0.85), yielding an optimal sample size of 20. The study was approved by the Ethics Board of the Faculty of Psychology and Educational Sciences, LMU Munich.

2.1.2 | Apparatus and stimuli

The experimental setup is illustrated in Figure 1. Participants sat comfortably in front of the visuo-tactile search display, with a viewing distance of approx. 55 cm to the central fixation marker, placing their fingertips softly on the top of the solenoid actuators. The stimuli were generated by a custom-made Matlab code (v. 2012) with the Psychtoolbox v. 308 (Kleiner et al., 2007). Visual and tactile stimuli were presented simultaneously during the search task. The visual items (each subtending 3.1° of visual angle, inter-item visual distance of approx. 3.9° on each side) were presented via a rear projector (Sharp XR-32X-L) onto a semi-transparent Plexiglas table (window size: 38.1° × 12.5°), oriented around 60° toward the participant. The tactile solenoids (Dancer Design), each of 1.8 cm in diameter, were placed directly below the visual items. The tactile vibrations were transmitted via a 10-channel amplifier to the solenoids. Among the stimuli, visual colors (blue, magenta) were kept isoluminant (36 cd/m^2), and tactile amplitudes were aligned (40 or 100 Hz). The basic features (color, shape, luminance, and vibration intensity) were selected based on a series of pilot experiments (see Appendix S1), such that search for the odd-one-out target and distractor stimuli used in the main experiment were similarly competitive for attentional selection.

To mask noise generated from the tactile vibrations, participants wore headphones (Philips SHL4000, 30-mm speaker drive) playing pink background noise (65 dBA) during the stimulus presentation.

2.1.3 | Procedure and design

To ensure good tactile discrimination, participants had to pass a tactile training (on the first day) before entering the formal experiment with EEG recording (on the second day). During training, participants learnt to detect a 100-Hz tactile vibration as a pop-out target among homogeneous 40-Hz distractors, with the target appearing in 50% of trials. In more detail, a trial started with a fixation cross presented for 500 ms, followed by the multi-modal search display for 250 ms. The displays consisted of 10 blue disks and 10 collocated vibrations, the latter delivered to participants' finger tips. Participants had to indicate whether or not a high-frequency (100-Hz) target vibration was present among the non-target (40-Hz) vibrations, by stepping a respective foot pedal as fast and accurately as possible. One pedal was mapped to "target-present" and the other to "target-absent," counterbalanced across participants. Participants performed at least eight training blocks of 100 trials each (50% target-present trials). The training session was terminated once participants achieved an accuracy higher than 80% in the last four blocks. Otherwise, additional block(s) were added until the participant reached the accuracy criterion. All participants met the criterion after practicing 9.5 blocks on average (SD = 2.3 blocks, range 8–15 blocks).[7]

Prior to the formal experiment, participants received another two-block refresher tactile training, to ensure that they could perform the tactile search as accurately as the visual search. In the formal experiment, they had to discern the presence (vs. absence) of a blue square target, while ignoring any other "deviant" distractors (see Figure 2, the left panel). Each trial started with a 500-ms central fixation cross, followed by the visual search array and the tactile vibrations for 250 ms. Participants then had to respond as fast and accurately as possible whether or not a target was present in the display, by pressing one foot pedal for "target-present" or the other for "target-absent." Following an incorrect response, participants received a warning beep (330 Hz, 300 ms) via the headphones. The next trial started after a random inter-trial interval of 950–1050 ms.

As already pointed out in the Introduction, we opted for a simple target (present/absent) detection task, rather than a compound-search task, which meant that we could also introduce a distractor-only (DO) condition alongside the target-only (TO) and target-plus-distractor (TD) conditions (where, in the latter, the target and distractor always appeared on opposite sides of the display). Of theoretical interest, this design enabled us to compare performance in the target-only and distractor-only conditions (in which there was only one odd-one-out item and thus no competition for selection) to the respective target-distractor conditions (in which there was competition).

The formal experiment consisted of 20 blocks, each of 90 trials, yielding a total of 1800 trials. Overall, there were 600 target-only trials (TO), 600 trials with both a target and a salient distractor, and 600 distractor-only trials (yielding a 2:1 ratio of target-present to target-absent

[7] In the follow-up Experiment 2, we reduced the training to dozens of trials (see Experiment 2 below for details) and extended it to visual search, in order to balance participants' pre-experimental experience with the visual and vibro-tactile stimuli. The results of Experiment 2 were essentially similar to those of Experiment 1, suggesting the long vibro-tactile training prior to Experiment 1 did not impact the way participants handled the various types of distractor.

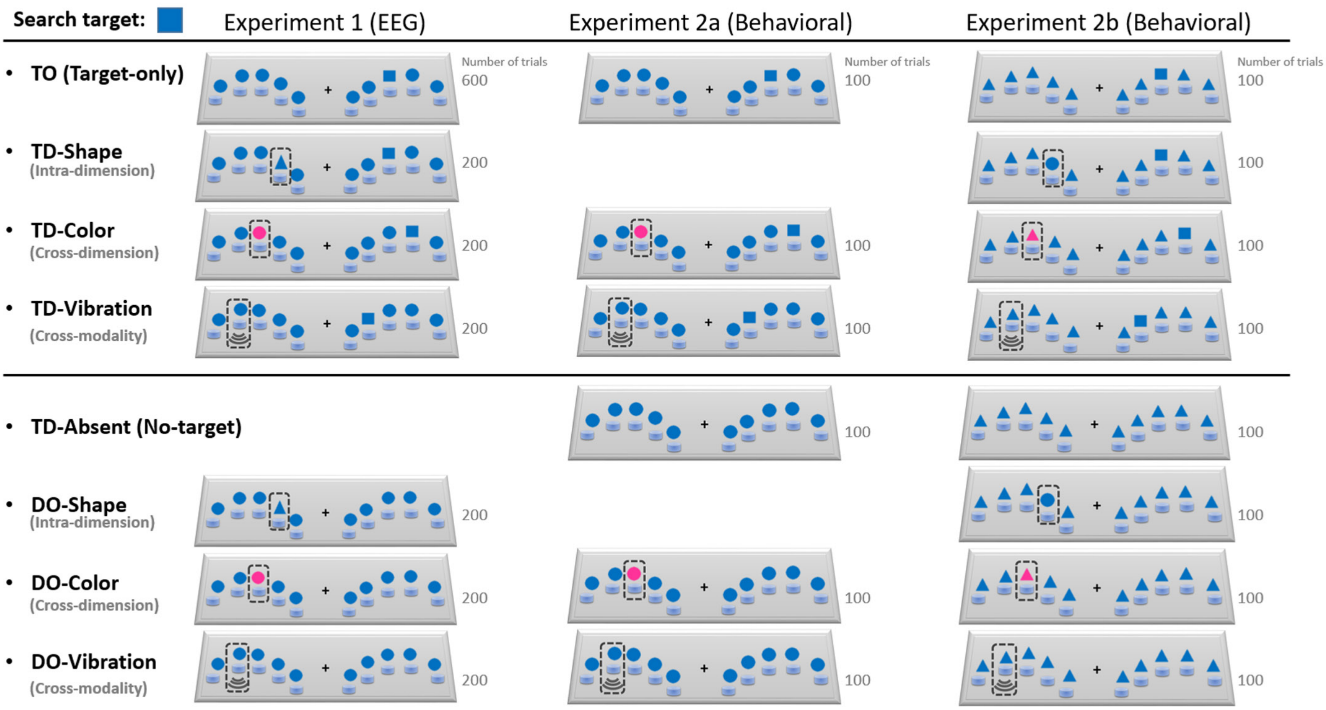

FIGURE 2 Types of search arrays used in Experiments 1 and 2. The target was a blue square across all experiments. The search arrays are grouped according to the response category: the upper panel were the target-present displays, and the lower panel the target-absent displays. There were three types of salient distractors: a shape-defined distractor (e.g., a blue triangle in Experiment 1 and a blue circle in Experiment 2b), a color-defined distractor (e.g., a red circle in Exp. 1 and 2a, a red triangle in Exp. 2b), and a vibro-tactile distractor (an odd-one-out, 100-Hz vibration, relative to the rest of the distractors receiving a homogeneous 40-Hz vibration). Those distractors are highlighted with an illustration-only dashed box. The target and the salient distractor could appear either on the left or the right side. When both were presented, they appeared on the opposite sides.

trials). The conditions were intermixed and randomized within a block. To counterbalance the left and right foot-pedal responses to target presence and absence, the response-to-pedal mapping was switched after completing 50% of the task (i.e., after the 10th block). Half of the participants started with pushing the left/right pedal for responding "target present/absent," and vice versa for the other half. To become familiar with the new response mapping, participants underwent at least one 50-trial practice block before both the first and the 11th block of the task proper, aiming for an accuracy higher than 80% (if they failed reach this criterion, additional practice block had to be performed); the practice trials were not included in the formal analyses.

There were seven distractor conditions (Figure 2b), including (1) TO ("TO" meaning *T*arget *O*nly): a shape-defined target only (a blue square); (2) TD-Shape: a target and an intra-dimensional distractor (a blue triangle, differing from the non-targets in the shape dimension); (3) TD-Color: a target and a cross-dimensional distractor (a magenta circle, differing from the non-targets in the color dimension); (4) TD-Vibration: a target and a cross-modal distractor (a high-frequency vibration, differing in modality); (5) DO-Shape ("DO" meaning *D*istractor *O*nly): target absence with an intra-dimensional distractor (a blue triangle); (6) DO-Color: target absence with a cross-dimensional distractor (a magenta circle); and (7) DO-Vibration: target absence with a cross-modal distractor (high-frequency vibration). In short, TD-Shape and DO-Shape trials included intra-dimension distractors, TD-Color and DO-Color trials cross-dimension distractors, and TD-Vibration and DO-Vibration trials cross-modal distractors.

2.1.4 | EEG recording and preprocessing

EEG data were continuously sampled at 1000 Hz using 64 Ag/AgCl active electrodes (acti-CAP system; Brain Products Munich), connected to a BrainAmp Standard amplifier, with an active reference located at FCz. The EEG preprocessing was conducted with EEGLAB v2020 (Delorme & Makeig, 2004).

In the offline data preprocessing, EEG data were re-referenced to mastoid channels (TP9 and TP10), downsampled to 500 Hz, applied an independent component analysis (ICA, extended infomax, Bell & Sejnowski, 1995; Lee et al., 1999) to remove vertical and horizontal eye movements artifacts (blinks and saccades). After the ICA artifact removal, the EEG data were filtered using a high-pass filter (1 Hz), followed by a low-pass filter (cut-off frequency 25 Hz), then epoched according to the seven distractor conditions with −1000 to 1000 ms segments, referenced to stimulus (target/distractor) onset. Then, we corrected the baseline of each trial with the range of −200 to 0 ms. Because we were interested in the event-related lateralizations (ERLs) induced by the lateral visual and tactile stimuli, we only selected the electrodes PO7, PO8, C3, and C4 for further analysis. Epoches were further rejected based on the following criteria: amplitudes larger than ±60 μV, peak-to-peak activity >100 μV, and flatline activity within the time window from −200 to 500 ms in each epoch. The average rejection rates were low overall, with 2.7% for TO (SD = 4.5%, max = 18.7%), 2.1% for TD-shape (SD = 3.8%, max = 15.9%), 2.3% for TD-Color (SD = 4.3%, max = 17.4%), 2.5% for TD-Vibration (SD = 4.3%, max = 17.1%), DO-Shape was 2.1% (SD = 4.3%, max = 19.3%), 1.9% for DO-Color (SD = 4.3%, max = 19.6%) 1.9% for DO-Vibration (SD = 4.6%, max = 20.8%).

2.1.5 | Statistical analysis

The statistical analyses of the behavioral data and the ERLs were performed using RStudio and JASP (2021, version 0.15). We applied the two-sigma rule to exclude trials with extreme, "outlier" RTs: slow responses (>1.22 s) and fast guesses (<0.1 s, the lower-bound of the two-sigma was negative). This led to the elimination of some 2.5% of trials, on average. Next, for both the RT and ERP analyses, trials were then sorted into the four target-present conditions (TO, TD-Shape, TD-Color, and TD-Vibration) and the three target-absent conditions (DO-Shape, DO-Color, and DO-Vibration).

To examine the ERLs, the contralateral and ipsilateral EEG waves were referenced either to the target location (in the target-present conditions) or the distractor location (in the target-absent conditions). All difference waves presented herein are the respective contralateral minus ipsilateral waves. Specifically, we were interested in the N2pc, CCP/CCN, CDA/cCDA, Ppc and P_D components, that is, the differences of the event-related potentials (ERPs) contralateral minus ipsilateral with reference to the location of the target (target-present conditions) and, respectively, the location of the distractor (target-absent conditions). The N2pc, Ppc, P_D, and CDA components were calculated from the parieto-occipital electrodes PO7/PO8, and the CCP/CCN and cCDA components from the medial central electrodes C3/C4.

Following the standard approach (Luck, 2005), we applied the mean-amplitude method, averaging amplitudes within a given time window, for all ERL analyses, with the windows being 100–200 ms for the Ppc; 200–300 ms for the N2pc; 50–250 ms for the CCP/CCN; and 300–400 ms for the late P_D. Recall that our task required a simple target-present/absent decision, which, at the post-selective stage, would only have involved checking whether any selected item was a target rather than a distractor, instead of extraction some additional, response-relevant target attribute as in the more frequently used "compound-search" tasks. Previous research has shown that (in contrast to early components such as the N2pc), the timing of late components varies depending on the complexity of the post-selective decisions required (Töllner et al., 2012). Accordingly, the minimal demands imposed by our simple detection tasks on post-selective processing should have been reflected in the timing of the CDA. Empirically, in our ERL data, the main differences were seen to emerge in the time window between 300 and 500 ms (rather than the [400,800] ms window often seen in studies with compound-search tasks). So, we selected [400, 500] ms for the CDA and [300, 500] ms for the cCDA.

We performed repeated-measures analyses of variance (ANOVAs) on the behavioral RTs, error rates, and ERL components, with the factors of Target Presence and Distractor Type. For separate analyses of the target-present and target-absent conditions, we performed ANOVAs with the single factor Distractor Type (including the TO condition as a factor level in target-present analyses). If necessary, we further conducted Bayesian repeated-measures ANOVAs to calculate the inclusion Bayes-Factor (BF_{incl}) for accepting the null hypothesis. The inclusion Bayes-factor quantifies the change from the prior inclusion odds to the posterior inclusion odds, reflecting the evidence in the data for including a given factor. We also used Holm tests for subsequent multiple comparisons, and when required, we included the simple *uncorrected* Bayes Factor (BF_U) based on the default simple t test with a Cauchy prior (0, $r = 1/\sqrt{2}$) from JASP (Wagenmakers et al., 2017).

2.2 | Results

2.2.1 | Behavioral results

Figure 3a depicts the mean RTs for correct-response trials and the respective error rates for the (four) target-present and the (three) target-absent conditions. Repeated-measures ANOVAs (Target (present, absent) × Distractor-Type (Shape, Color, Vibration)) revealed the two main effects and the interaction to be significant, for both the mean RT and the accuracy scores (see Table 1). RTs were significantly slower on

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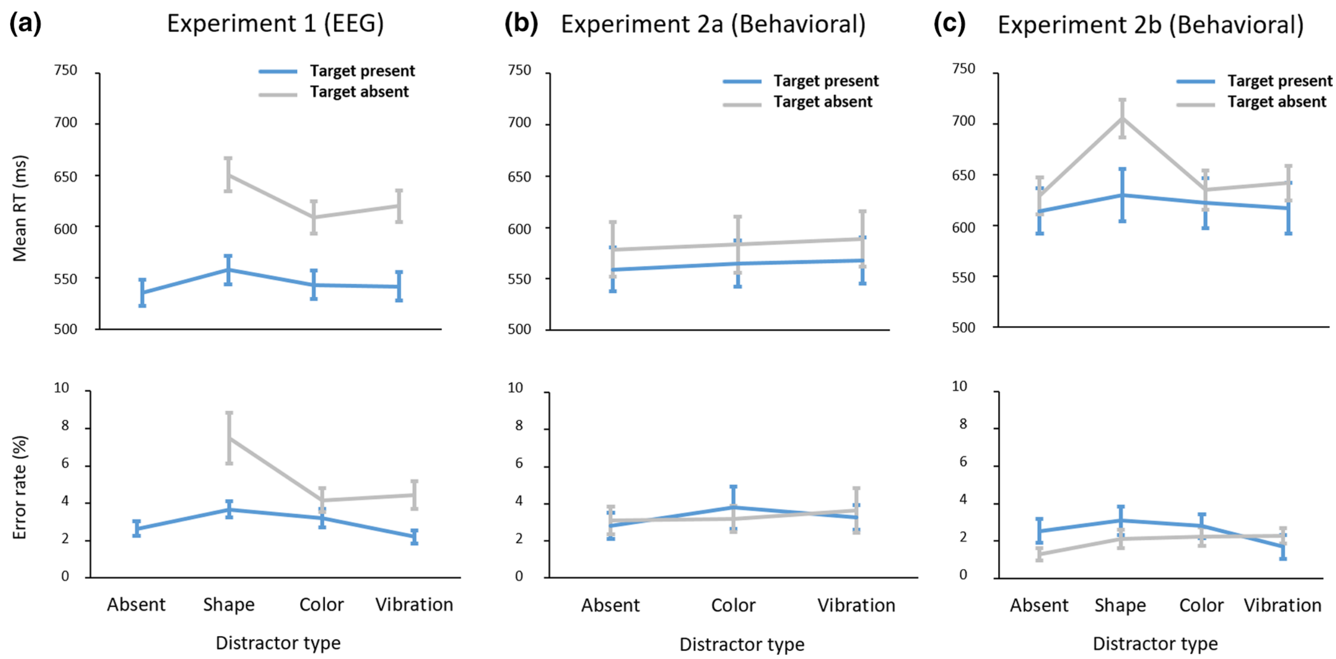

FIGURE 3 Mean RT (upper panel) and error rate (lower panel) as a function of the distractor type, separately for target-present (blue) and target-absent (gray) trials, separated for individual experiments. Error bars represent one standard error of the mean.

target-absent versus target-present trials – a standard effect seen in visual search tasks (including search for pop-out targets). The error rates were also higher in the target-absent conditions (false-alarm rates). While being indicative of participants endeavoring to minimize target-miss errors (by operating a bias toward responding "target-present"), this effect may partly also be owing to the high target prevalence (67%), inducing more false-alarm responses on target-absent trials. The significant interactions in both RTs and error rates were mainly attributable to the condition with a shape-defined distractor. Post-hoc comparisons revealed the shape distractor to particularly slow RTs in the absence versus the presence of a target in the display (RT slowing on target-absent vs. -present trials: Shape 93 ms, Color 66 ms, Vibration 78 ms): Shape versus Color (28 ms, $p < .001$), Shape versus Vibration (15 ms; $p < .001$), Color versus Vibration (5 ms, $p = .060$). The error rates showed a similar effect pattern: the false-alarm- to miss-rate difference was numerically greater with a shape distractor in the display (difference = 3.8%) compared to a vibration distractor (difference = 2.2%) and, respectively, a color distractor (difference = 1.0%).

Focusing on the target-present trials and comparing the TO (baseline) condition against the three TD conditions revealed a significant RT cost only for the TD-Shape condition (difference = 22 ms, $p = .001$), but not for the TD-Color (difference = 8 ms, $p = .542$) and TD-Vibration (difference = 6 ms, $p = .542$) conditions; this cost cannot be attributed to a difference in the error rates, which were comparable among all (i.e., the TO and the three TD) conditions ($p > .9$).

A further analysis examining how distractor interference – or, respectively, participants' ability to handle distractors – changes with experience revealed little evidence of participants learning to mitigate the interference caused by Shape distractors (especially on DO-Shape trials) with increasing time-on-task. In contrast, on distractor-only (DO) trials, the color and vibration distractors showed a decrease in interference over time-on-task. This suggests that while they may have caused some "distraction" early on during task performance, participants became more adept at handling these distractors through experience. (See Appendix S2 for details.)

Interim discussion of behavioral results

The fact that, in our detection task, the target-absent were generally slower than the target-present RTs is not surprising: this *target effect*, is ubiquitously observed, even in pop-out detection tasks (e.g., Chun & Wolfe, 1996; Krummenacher et al., 2002; Müller et al., 1995), and it may have been exacerbated by the fact that target-present trials (2/3) were twice as likely than target-absent trials (1/3) in Experiment 1. Given that, in detection tasks, participants strive to avoid target-miss errors, they tend to respond target-absent only after a certain time has elapsed within which even the "slowest targets" have been experienced to emerge (i.e., the waiting time is set according to the distribution of task-relevant "target activity" sampled on target-present trials). Evidence of this comes from

TABLE 1 Main and interaction effects in the RT (left panel) and error-rate (right panel) ANOVAs of performance in Experiments 1, 2a, and 2b.

RT	*df*	*F*	*p*	η_p^2	BF_{incl}	Error rate	*df*	*F*	*p*	η_p^2	BF_{incl}
Experiment 1						*Experiment 1*					
Target	1, 20	154.34	<.001***	0.885	>100	Target	1, 20	18.12	<.001***	0.475	>100
Distractor Type	2, 40	70.64	<.001***	0.779	>100	Distractor type	2, 40	8.45	<.001***	0.297	88.337
Target × Distractor Type	2, 40	12.23	<.001***	0.379	>100	Target × Distractor Type	2, 40	4.23	<.001***	0.174	16.08
Experiment 2a						*Experiment 2a*					
Target	1, 17	7.50	.014*	0.306	2.701	Target	1, 17	<0.01	.982	<0.001	0.214
Distractor Type	2, 34	13.03	<.001***	0.434	63.520	Distractor type	2, 34	0.406	.670	0.023	0.122
Target × Distractor Type	2, 34	0.21	.805	0.013	0.513	Target × Distractor Type	2, 34	0.513	.603	0.029	0.032
Experiment 2b						*Experiment 2b*					
Target	1, 17	13.89	.002**	0.450	>100	Target	1, 17	1.21	.286	0.067	0.562
Distractor type	2, 34	92.60	<.001***	0.845	>100	Distractor Type	2, 34	1.84	.152	0.098	0.372
Target × Distractor Type	2, 34	64.32	<.001***	0.791	>100	Target × Distractor Type	2, 34	2.93	.042*	0.147	0.798

Note: Asterisks (*) denote the level of significance: $p < .05$*, $p < .01$**, $p < .001$***.

an analysis of the singleton-only RTs as a function of the eccentricity of the target (see Appendix S3): the further out a target was presented, the slower the detection RTs. Of note, though, the eccentricity gradient was relatively shallow, with a slowing of only some 4.0 ms per degree of visual angle. Interestingly, there was no such gradient for distractor-only trials (i.e., the function relating target-absent RTs to distractor eccentricity was flat). But the level of the target-absent RTs (i.e., the intercept of the function) was somewhat slower than the slowest target-present RTs, that is, the RTs to the most peripheral target. Of note, this (modestly) elevated level was specific to DO-Color and DO-Vibration distractors (the elevation disappeared when the target prevalence was reduced to 50% in Experiment 2, see Figure S3). With DO-Shape distractors being the only stimulus in the display, the level of target-absent RTs was greatly (rather only modestly) elevated, by some 68 ms relative to DO-Color and DO-Vibration distractors (even in Experiment 2b). This increase is indicative of the additional time the slowest target signal takes to emerge when the distractor engages attentional resources. In contrast, the lower level with DO-Color and DO-Vibration distractors would reflect the additional time taken by the slowest target signal to emerge in the (near-) absence of the distractor engaging attention.

This dynamics of decision making would explain why the shape distractor amplified the Target effect, that is: why the shape distractor caused some interference on target-present trials (on average, across the target-eccentricity conditions, around 25 ms compared to the TO-condition), but at least twice this effect on distractor-only target-absent trials (increase of at least 50 ms compared to the DO-Color condition). We take the difference to reflect the additional time required when the Shape distractor more or less fully engages attention on target-absent trials relative to when it engages only a fraction of the attentional resources (due to concurrent or statistical attention sharing with the target) on target-present trials.

In contrast, Color and Vibration distractors caused no significant slow-down on target-present trials, that is, cross-dimension and cross-modal distractors did not reliably compete with attentional selection of the target. This suggests that there was also relatively little extra cost, beyond the general response slowing, on target-absent trials, when the distractor faced no competition from a target.

2.2.2 | Electrophysiological results

In the ERL analysis, we were most interested in the N2pc and CCP/CCN components. The N2pc, derived from electrodes PO7/PO8, reflects visual attentional deployment; and the CCP, derived from C3/C4, reflects tactile

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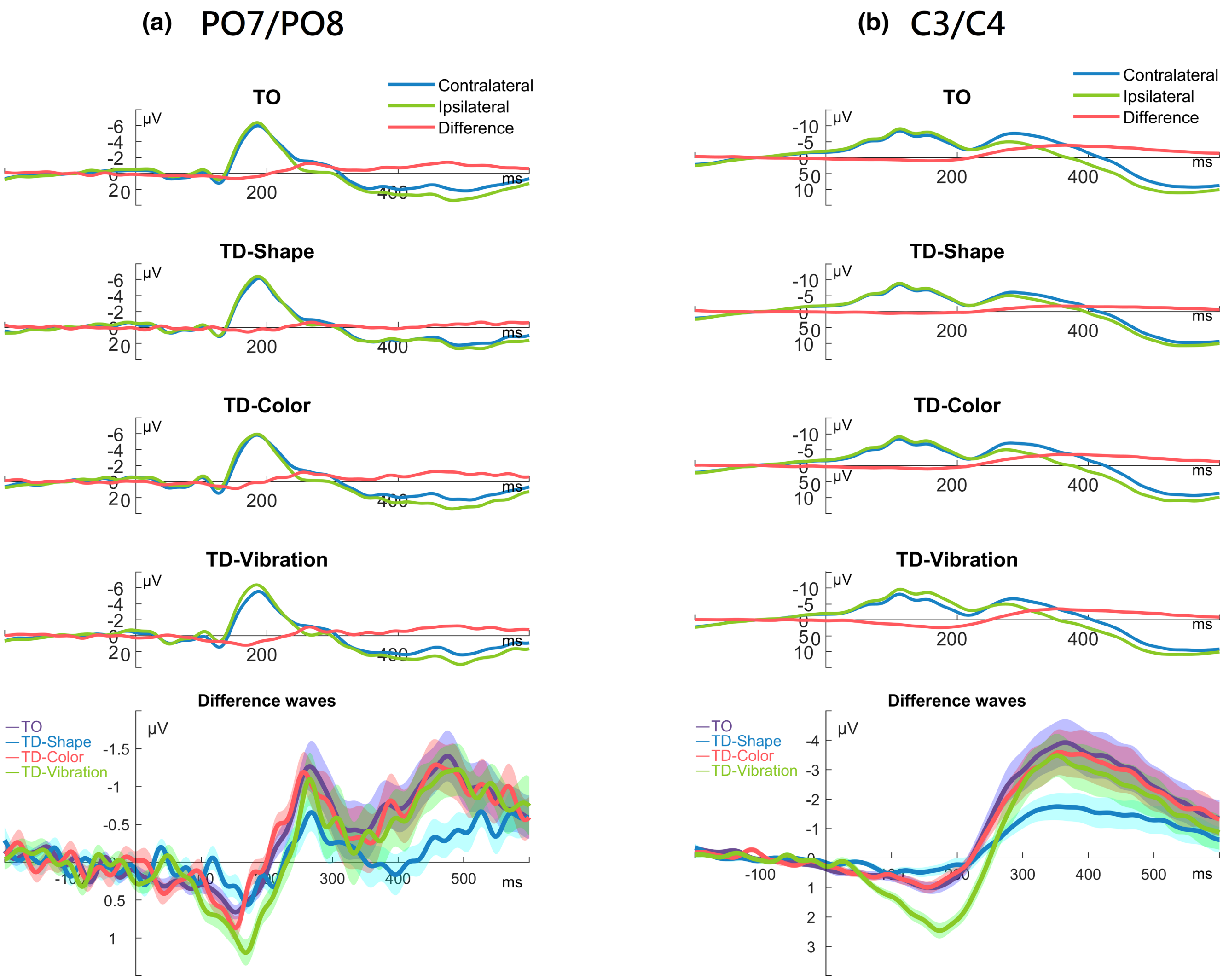

FIGURE 4 ERPs elicited contra- and ipsilateral to the target location for the four types of target-present trials (factor: Distractor Type) from electrodes PO7/PO8 (a) and, respectively, C3/C4 (b). Difference waves indicate contralateral minus ipsilateral waves, referenced to the target location/side (for the target-present trials), with distractors always appearing on the opposite side. 0 ms on the x-axis marks target/distractor onset. The shaded area enveloping each waveform depicts the standard error of the mean.

sensation. Given that the interpretation of the lateralized components depends on the reference – target or, respectively, distractor – we partitioned the seven conditions into two categories: the target-present conditions, with the target as reference (TO, TD-Shape, TD-Color, TD-Vibration; see Figures 4 and 5), and the target-absent distractor-only conditions, with the distractor as reference (DO-Shape, DO-Color, DO-Vibration; see Figures 6 and 7), and report the results in separate subsections.

ERLs for the target-present conditions

Figure 4 depicts the contra- and ipsilateral ERPs and their difference waveforms from PO7/PO8 and, respectively, C3/C4. As can be seen from the left panel, the difference waves reveal a prominent N2pc around 200–300 ms post stimulus, followed by a CDA component around 400–500 ms. For the central electrodes C3/C4 (the right panel), difference waves show a prominent CCP component specifically for the TD-Vibration condition, followed by a cCDA component around 300–500 ms. We conducted one-way (Distractor-Type) ANOVAs for mean amplitudes of individual components; the results are summarized in Table 2.

N2pc. The posterior N2pc is the key signature of lateralized attentional deployment. Figure 5a depicts the mean N2pc amplitudes for the four target-present conditions. The amplitudes differed significantly among distractor types (Table 2). Compared to the baseline target-only (TO) condition, the amplitude of the (target-referenced) N2pc was significantly reduced when a shape distractor (difference = 0.501 μV, $p = .011$, $BF_U = 3.721$) on the side opposite to the target, but not when a color was presented (difference = 0.024 μV, $p > .9$, $BF_U = 0.232$). This pattern suggests that the shape (i.e., intra-dimension) distractor diverted attention away from the target, whereas the color

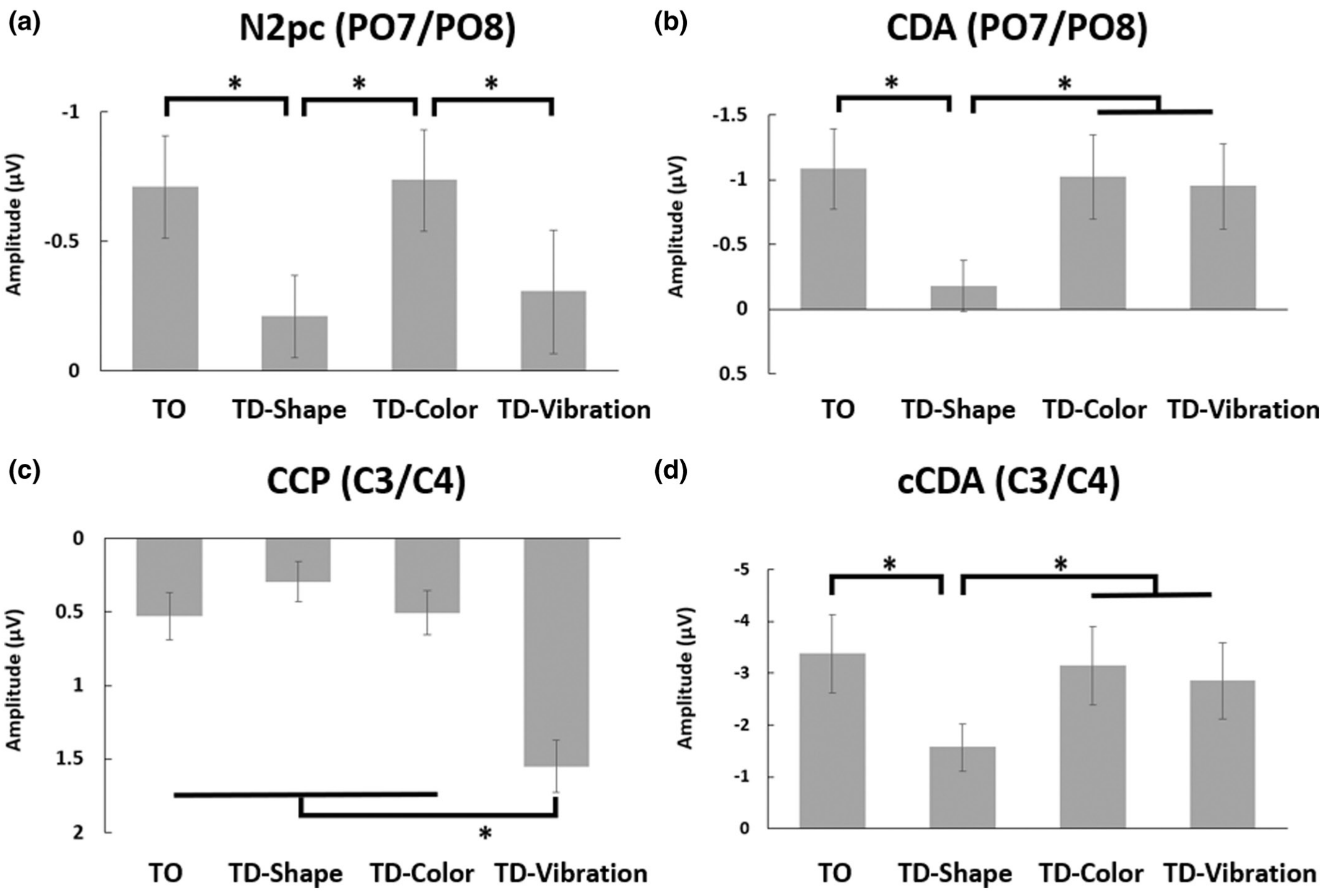

FIGURE 5 Amplitudes of the ERL components from PO7/PO8 and, respectively, C3/C4 on target-present trials, separately for the four distractor conditions. (a) N2pc amplitude within the 200–300 ms time window. (b) CDA amplitude in the 400–500 ms window. (c) CCP amplitude within the 50–250 ms time window. (d) cCDA amplitude in the 300–500 ms window. Error bars depict the standard error of the mean. Asterisks (*) indicate $p < .05$.

(i.e., cross-dimension) distractor was effectively kept out of the competition for selection. There was also a significant reduction of the N2pc mean amplitude with the vibrotactile (i.e., cross-modality) distractor (difference = 0.405 µV, $p = .037$, $BF_U = 22.5$). However, considering the *peak* amplitude, there was no significant reduction in the (*peak*) amplitude of the N2pc in the TD-Vibration versus the TO condition (difference = 0.172 µV, $p = .35$, see Figure 4a). Accordingly, the reduction of the *mean* amplitude of the N2pc resulted from the constriction of its spread – probably brought about by the propagation of CCP activity from the sensorimotor (C3/C4) to the occipital region (PO7/PO8), which distorted the forms of the Ppc and the N2pc. That is, the reduction in the mean amplitude of the N2pc is most likely attributable to the positive voltage spreading from the sensorimotor area, which exhibits early activation in response to the tactile distractor (see difference waves in Figure 4, and analysis of the CCP below).

CDA and cCDA. Figure 5b depicts the mean CDA amplitude for the four target-present conditions. Again, the significant difference (see Table 2) was mainly caused by the markedly reduced CDA amplitude in the TD-Shape condition relative to the TO condition (difference = 0.907 µV, $p < .001$), while there was no reduction of CDA in the TD-Color ($p > .9$, $BF_U = 0.245$), and TD-Vibration ($p > .9$, $BF_U = 0.736$). This pattern can be taken to suggest that the shape-target and the shape-distractor were competing equally for working-memory resources for the target identification in the TD-Shape condition, but not in the other conditions.

The cCDA (time window 300–500 ms), depicted in Figure 5d, mimics the pattern of the CDA (Figure 5b): a significant main effect of Distractor Type (Table 2) was mainly caused by the amplitude being smallest in the TD-Shape (intra-dimension) condition, compared to the baseline target-only (TO) condition (difference = 1.810 µV, $p < .001$, $BF_U = 20.9$); in contrast, there was no significant amplitude reduction in the TD-Color ($p = .885$, $BF_U = 0.375$) and the TD-Vibration ($p = .513$, $BF_U = 11.0$) condition relative to the TO baseline (the discrepancy

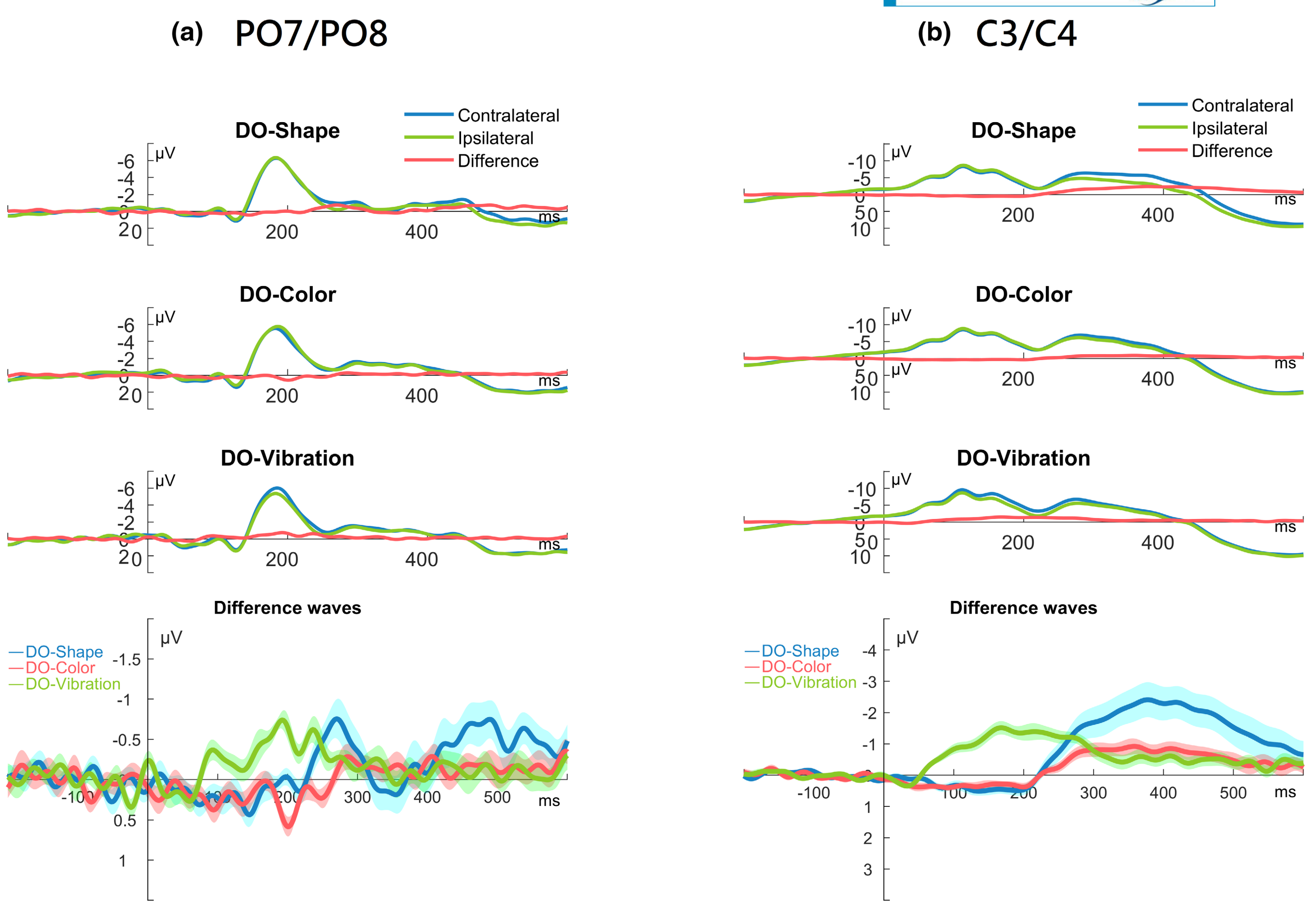

FIGURE 6 ERPs elicited contralateral and ipsilateral to the distractor location for the three types of target-absent trials (factor: Distractor Type) from electrodes PO7/PO8 (a) and, respectively, C3/C4 (b). Difference waves indicate contralateral minus ipsilateral waves, referenced to the distractor location/side (for the target-absent trials). 0 ms on the x-axis marks distractor onset. The shaded area enveloping each waveform depicts the standard error of the mean.

between the Holm test and the Bayes factor is likely attributable to the latter being an uncorrected value).

CCP. The CCP from C3/C4, depicted in Figure 5c, reflects sensorimotor activity caused by the salient vibrotactile-distractor stimulation. As can be seen, when one salient, high-frequency vibration among other, low-frequency vibrations was delivered to participants' fingers, this TD-Vibration distractor elicited a CCP (Table 2). The post hoc tests confirmed the CCP amplitude was largest in TD-Vibration condition compared to the TO (difference = 1.021 μV, $p < .001$), TD-Shape (difference = 1.256 μV, $p < .001$), and TD-Color (difference = 1.044 μV, $p < .001$) conditions. The CCP amplitudes were comparable among the latter three conditions ($ps > .137$).

ERLs for the target-absent conditions

For the three target-absent conditions, we computed the ERLs relative to the distractor location. In addition to subjecting them to Distractor-Type (DO-Shape, DO-Color, DO-Vibration) ANOVAs, we also examined their amplitude differences relative to the (target-referenced) TO condition, in which there was likewise only one singleton in the display (the target, rather than a distractor). The waveforms depicted in Figure 6 show the posterior contralateral negativity (N2pc) in the parietal-occipital area (PO7/PO8, Figure 6a) and, respectively, the central contralateral negativity (CCN) in the central area (C3/C4, Figure 6b). Note that the tactile CCN (DO-Vibration, negative values) here is opposite in polarity to the CCP described in the above analyses of the target-present conditions (TD-Vibration, positive values). Figure 7 presents the mean amplitudes of critical distractor-referenced ERL components: the N2pc, Ppc, late P_D, CDA, cCDA, and CCN.

N2pc. As can be seen from Figure 7a, relative to the DO-Color condition, the N2pc amplitudes were more negative-going for the DO-Shape condition (−0.33 μV, $p < .05$) and the DO-Vibration condition (−0.37 μV, $p < .01$), accounting for the significant Distractor-Type effect (Table 2). This result pattern suggests that, in the absence of a target, more attentional resources

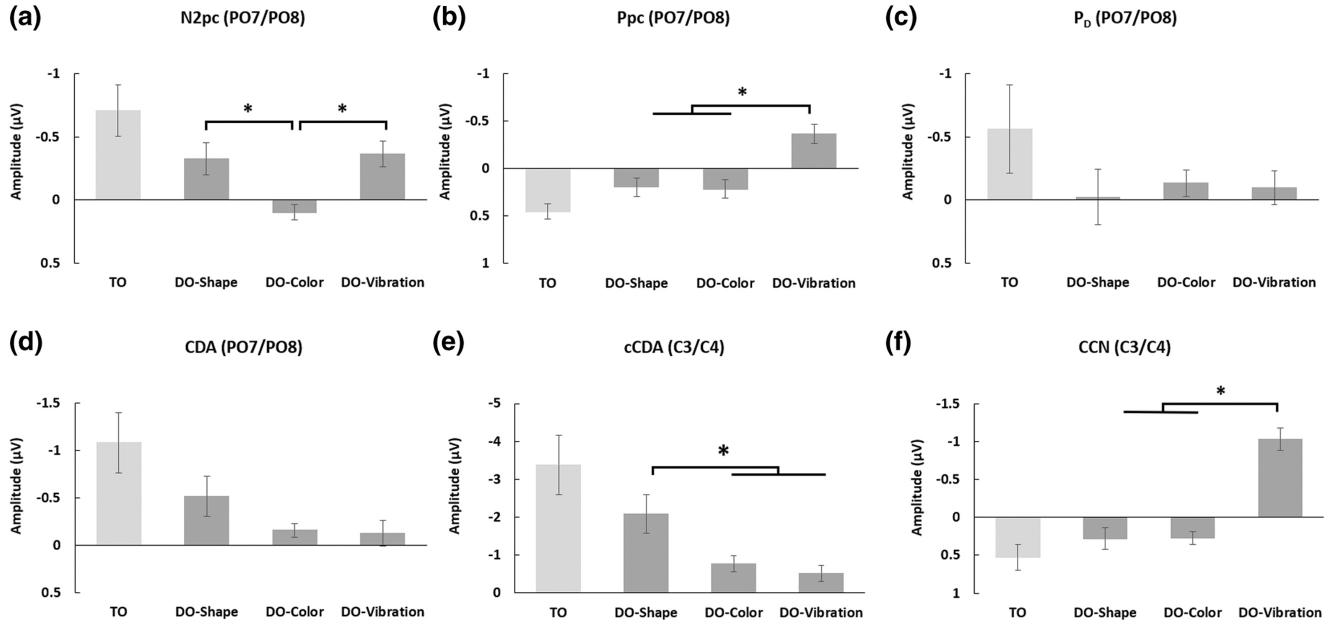

FIGURE 7 Amplitudes of the ERL components from PO7/PO8 and C3/C4 on target-absent trials, separately for the three distractor conditions; for reference and comparison, the ERLs are also depicted for the target-only (TO, light gray) condition, in which displays likewise contained only one singleton item, the target. (a) N2pc amplitude within the 200–300 ms time window. (b) Ppc amplitude in the 100–200 ms time window. (c) P_D amplitude in the 300–400 ms time window. (d) CDA amplitude in the 400–500 ms time window. (e) cCDA amplitude in the 300–500 ms time window. (f) CCN amplitude in the 50–250 ms time window. The error bars depict the standard error of the mean. Asterisks (*) indicate $p < .05$.

were deployed to the shape – and seemingly the vibration – distractor than to the color distractor. The N2pc amplitude was also more negative-going in the TO condition (−0.711 µV, $p < .001$), without differing significantly from the DO-Shape and DO-Vibration conditions ($ps > .059$). Of note, the marked N2pc amplitude elicited by the vibration distractor is likely caused by the spreading of activity from the early lateralized sensorimotor response (CCP/CCN) generated by the vibrotactile stimulation (see Figures 5c and 7f). Accordingly, the lack of a reliable difference between the TO and DO-Shape conditions would indicate that the shape distractor engaged attention to a similar degree as the shape-defined target.

Ppc and P_D. Figure 7b depicts the Ppc amplitudes in the parietal-occipital area (PO7/PO8). There was a significant Distractor-Type effect (Table 2), characterized by a distinct negativity with the vibrotactile distractor, as compared to the Shape and the Color distractors and the TO target ($ps < .001$). Both the Shape and Color distractors displayed positive-going deflections, which differed (marginally) significantly from zero (Shape: 0.194 µV, $p = .054$; Color: 0.214 µV, $p = .034$). For TO targets, the amplitude was also significantly positive (0.451 µV, $p < .001$), though only numerically larger compared to those with the DO-Shape and DO-Color distractors ($ps > .198$). Given that the DO-Shape and DO-Color distractors show a similar positivity to that elicited by the TO target, it is unlikely that they reflect a specifically distractor-related process, that is, early (proactive) suppression of visual distractors; instead unless one assumes that the target is also suppressed.

We also looked for potential P_D components in the three distractor-type conditions. As can be seen from Figure 7c, there was no evidence of a P_D in any of the distractor-only conditions (Table 2): the mean amplitudes tended to be numerically negative (rather than positive), though none differed from zero ($ps > .116$).

CDA and cCDA. Figure 7d,e depict the mean amplitudes of the CDA for the three distractor-only conditions, along with the TO baseline condition, in the parietal-occipital region and, respectively, the mean cCDA amplitudes in the central region. As can be seen, the CDA and, in cCDA amplitudes were larger for the DO-Shape condition compared to DO-Color and DO-Vibration conditions. However, the main effect of Distractor Type turned out significant only for the cCDA, and not the CDA (see Table 2), with the cCDA effect largely due to the single large negative amplitude in the DO-Shape condition (−2.048 µV) versus the other DO conditions ($ps < .007$). Note, though, that all CDA and cCDA amplitudes were significantly negative (except

TABLE 2 Main effects for the ERL components in Experiment 1.

Component	Time window	*df*	*F*	*p*	η_p^2	BF_{incl}	Amplitude (μV): Baseline (TO)	Amplitude (μV): intra-dimension (shape)	Amplitude (μV): cross-dimension (color)	Amplitude (μV): cross-modality (vibration)
							Mean (SD)			
Target-present (Four levels: TO, TD-Shape, TD-Color, and TD-Vibration)										
N2pc (PO7/PO8)	200–300 ms	3, 60	5.992	.001**	0.231	26.733	−0.711 (0.911)**	−0.210 (0.732)	−0.736 (0.897)**	−0.306 (1.097)
CDA (PO7/PO8)	400–500 ms	3, 60	9.492	<.001***	0.322	>100	−1.086 (1.419)**	−0.180 (0.903)	−1.019 (1.498)**	−0.950 (1.514)**
CCP (C3/C4)	50–250 ms	3, 60	47.734	<.001***	0.705	>100	0.527 (0.737)**	0.292 (0.613)*	0.504 (0.697)**	1.548 (0.808)***
cCDA (C3/C4)	300–500 ms	3, 60	9.223	<.001***	0.316	>100	−3.373 (3.494)***	−1.563 (2.088)**	−3.143 (3.474)***	−2.852 (3.355)***
Target-absent (Three levels: DO-Shape, DO-Color, and DO-Vibration)										
N2pc (PO7/PO8)	200–300 ms	2, 40	7.513	.002**	0.273	52.670	−0.711 (0.911)**	−0.328 (0.565)*	0.097 (0.279)	−0.368 (0.455)**
Ppc/early P_D (PO7/PO8)	100–200 ms	2, 40	9.114	<.001***	0.313	>100	0.451 (0.358)***	0.194 (0.433)	0.214 (0.430)*	−0.368 (0.464)**
P_D (PO7/PO8)	300–400 ms	2, 40	0.152	.859	0.008	0.148	−0.561 (1.565)	−0.023 (0.981)	−0.133 (0.474)	−0.098 (0.602)
CDA (PO7/PO8)	400–500 ms	2, 40	2.506	.094	0.111	0.967	−1.086 (1.419)**	−0.518 (0.966)*	−0.159 (0.318)*	−0.125 (0.614)
CCN (C3/C4)	50–250 ms	2, 40	34.104	<.001***	0.630	>100	0.527 (0.737)**	0.278 (0.616)	0.270 (0.383)**	−1.033 (0.666)***
cCDA (C3/C4)	300–500 ms	2, 40	7.759	.001**	0.280	45.697	−3.373 (3.494)***	−2.084 (2.315)***	−0.762 (0.963)**	−0.517 (0.920)*

Note: Asterisks (*) denote the level of significance: $p < .05$*, $p < .01$**, $p < .001$***. The asterisks at the right panel indicate that the mean (amplitude) differs from 0 (one-sample *t* tests).

that of the CDA in the DO-Vibration condition), but the amplitudes were significantly smaller even in the DO-Shape versus the target-only (TO) conditions. Overall, this pattern indicates that especially Shape-distractor singletons had gained access to the post-selective (vWM) processing stage, though their "representation" at this stage appeared to be less compared to that of target singletons.

CCN. Figure 7f depicts the CCN amplitudes in the central area (C3/C4) for the three distractor types, along with the amplitude for TO targets. As can be seen, the CCN amplitudes differed among three distractor types (Table 2): the DO-Vibration distractors elicited a strong negativity (−1.033 μV, $p < .001$), whereas the DO-Shape (0.278 μV) and DO-Color (0.270 μV) distractors showed a positive-going deflection (i.e., no "CCN"). For the latter two conditions, the amplitudes were comparable to the positive CCP component in the TO target condition ($ps > .440$). Thus, just like the CCP on target-present trials, the CCN in the DO-Vibration condition reflects sensorimotor activity solely driven by the salient vibrotactile distractor.

Comparisons among ERLs

One theoretically important issue relates why the difference in N2pc amplitude occurred among different distractor conditions. A significant reduction (it was approximately halved) was observed in the TD-Shape condition, where there was a shape distractor on the opposite side to the shape target, relative to the TO condition, where the shape target was the only singleton in the display (see Figure 5a). Given that the shape distractor also elicited an N2pc when presented alone (see Figure 7a), the diminished N2pc in the TD-Shape condition can be attributed to the shape distractor drawing attention away from the shape target – that is, in terms of Zivony et al. (2018), the "attentional enhancement" of the distractor signal comes at the expense of the "enhancement" for the target signal, a process known as "normalization" (Louie et al., 2013; Reynolds & Heeger, 2009). This trade-off could be either due to attention being concurrently divided, or "shared," in some ratio between the shape distractor and the shape target; or, alternatively, due to trial-wise statistical averaging, with attention being fully deployed to, or "captured" by, the target on some proportion of trials and to the distractor on the other trials. In an attempt to decide between these two alternatives, we split the TD-Shape trials into the fastest trials (the first 25% percentile of the RT distribution) and the slowest trials (the last 25% percentile) and compared the corresponding (N2pc) difference waves (McDonald et al., 2013). On fast-RT trials, one would expect that attention was immediately deployed to the target, according to the discrete-attentional-capture account; in contrast, on slow-RT trials, attention would have been first deployed to the distractor, upon being disengaged and re-allocated to the target. This would predict the target-referenced N2pc to emerge and/or peak earlier on fast- relative to slow-RT trials. Alternatively, assuming a continuous "attention-sharing" account, the distribution of attentional resources between the target and Shape distractor may have been variable, in particular: relatively more resources may have been allocated to the target, and correspondingly less to the distractor, on fast- versus slow-RTs trials, which would be expressed in an N2pc amplitude difference. However, as can be seen from Figure 8, there was neither an N2pc timing nor an amplitude difference between fast and slow trials: latencies (fast vs. slow), 272 vs. 265 ms; amplitudes, −0.75 vs. −0.79 μV, *t*s $(21) < 1.295$, *p*s $> .210$. The lack of a timing difference would be more consistent with an attention-sharing account, and, consequently, the lack of an amplitude difference would argue in favor of a near-equal sharing of attentional resources between the target and Shape distractor on TD trials (for evidence that spatial attention may be divided between non-contiguous locations, see, e.g., the visuals steady-state evoked potential study of Müller, Malinowski, et al., 2003).

2.3 | Discussion

In Experiment 1, we systematically varied the salient distractors in a task requiring (present/absent) detection of a fixed odd-one-out target shape in a visuo-tactile display array. The target was a blue square, and non-targets were all blue circles except for, on 2/3 of the trials, one odd-one-out distractor, defined either by shape (intra-dimension distractor), color (cross-dimension distractor), or vibro-tactile frequency (cross-modal distractor). Behaviorally, the intra-dimension (shape) distractor interfered substantially with target detection, slowing responses; the cross-dimension (color) and cross-modal (vibro-tactile) distractors, by contrast, produced little RT interference (no discernible interference on target-present trials). Electrophysiologically, this pattern was mirrored in the N2pc and the CDA/cCDA components: the target-referenced N2pc, CDA, and cCDA amplitudes were reduced in the presence of an intra-dimension (TD-Shape) distractor, compared to the target-only (TO) condition, while cross-dimension (TD-Color) and cross-modality (TD-Vibration) distractors produced no or little reduction in those components (the small reduction of the N2pc in the TD-Vibration condition was likely caused by the spreading of activity from the earlier CCP). The comparable activities of the TD-Color and the TD-Vibration condition to the TO condition indicates that salient cross-dimension and cross-modality distractors can be relatively effectively suppressed (Sawaki & Luck, 2010).

When the search array contained just a distractor singleton (among the non-target items) and no target, only the intra-dimension distractor elicited a marked distractor-referenced N2pc and a marked cCDA. The cross-dimension distractor induced no N2pc; and the vibro-tactile distractor elicited a robust CCN, though only a numerical N2pc.

Overall, these behavioral and electrophysiological result patterns are consistent with the notion of dimension/modality weighting: Cross-dimension and cross-modality distractor can be effectively suppressed by dimension/modality-based down-weighting of their feature-contrast signals (as a result of which they influence the accrual of activity on the attentional-priority map only weakly), whereas intra-dimension distractors cannot be down-weighted as doing so would compromise target detection. Consequently, intra-dimension

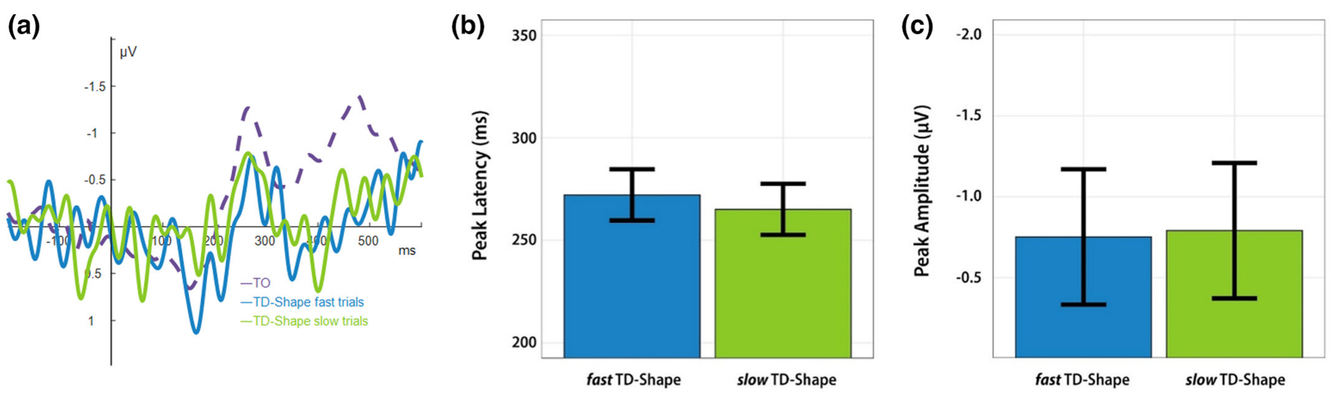

FIGURE 8 (a) Contralateral minus ipsilateral difference waves, referenced to the target-side, for the fastest-RT trials (blue) versus the slowest-RT trials (green), with the target-only (TO) baseline (dashed) for comparison. (b) Mean N2pc (peak) latencies and (c) N2pc (peak) amplitudes for the three conditions; error bars depict the standard error of the mean.

distractors necessarily interfere more with target selection compared to cross-dimension and cross-modality distractors.

3 | EXPERIMENT 2

However, rather than arguing in favor of the DWA/MWA, the strong interference caused by the intra-dimension triangle distractor observed in Experiment 1 may be attributable to target-distractor feature similarity in the shape domain, as the triangle distractor and the square target shared some common features, such as the horizontal line forming the base of the two shapes and the presence of corner junctions (albeit of different angles) at its ends. Target-distractor feature similarity could have played a crucial role if participants operated in "feature-search" – as opposed to "singleton-detection" – mode (Bacon & Egeth, 1994; Liesefeld, Liesefeld, Pollmann, & Müller, 2019; Theeuwes et al., 2022), that is, if they set up a search template specifying the critical features distinguishing the target from the non-target (including distractor) items. Thus, if observers did operate in feature-search mode but failed to tune the search template specifically to the "square" features of the target that distinguish it from the "triangle" distractor, the latter might have been selected inadvertently on some proportion of the trials, leading to interference. In contrast, the color and vibrotactile distractors would have caused no interference because they shared no features with the target description – thus explaining the effect pattern seen in Experiment 1. To rule out an account of our interference pattern in terms of target-distractor feature similarity, we conducted two behavioral control experiments, Experiments 2a and 2b. In Experiment 2a, we simply omitted the intra-dimension (i.e., shape) distractor condition and added a pure target-absent condition (see middle panel in Figure 2 above) – the response requiring a target-present/absent decision. Given the lack of an intra-dimension distractor, observers would have had less incentive, or pressure, to adopt a feature-search mode, rather than a singleton-detection mode; accordingly, on search-mode accounts, the color and vibrotactile distractors would now be expected to have a greater potential to cause interference. In Experiment 2b, we re-introduced the intra-dimension (shape) distractor but made this a circle, which had no (horizontal base or line junction) features in common with the target square – allowing the search template to be tuned uniquely to all features defining the target. Thus, if the (circular) shape distractor, but not the color or vibrotactile distractor, produced significant interference in Experiment 2b, this would argue against target-distractor similarity being the cause of the pattern of interference effects (while further supporting the view that participants operated in singleton-detection mode). In addition to these critical manipulations in Experiments 2a and 2b, we equalized the ratio of target-present:-absent trials to 1:1, to examine how this would influence the effects on the target-absent RTs.

3.1 | Method

3.1.1 | Participants

In total, 36 healthy participants took part in the Experiments 2a and 2b (18 participants each, mean age of 26.7 years, range 20–37 years; 25 females, 11 males).

3.1.2 | Training

In Experiment 2, the training period was shortened compared to Experiment 1. Following a block of 20 trials, we checked whether search accuracy had reached the criterion of >80% correct responses. If so, the training stopped. Otherwise, another block of 20 trials was administered, and so forth. Participants reached the criterion with one or two blocks for visual target training and three to four blocks (maximum seven blocks) with tactile target training. Differing from practice in Experiment 1, participants trained the tactile search and visual search in separate blocks to promote a "singleton-detection" mode. In the tactile pop-out training, the target was the same high-frequency vibration among nine low-frequency vibrations as in Experiment 1. In visual pop-out training, the displays were essentially also the same as in Experiment 1, except that participants only practiced detecting a magenta ("color-distractor") circle and blue ("shape-target") square in Experiment 2a (which did not include a shape distractor), and magenta ("color-distractor") triangle and blue ("shape-target") circle in Experiment 2b (because of the swapping of the non-target and target shapes relative to Experiment 1).

3.1.3 | Design

The design of Experiment 2a was essentially the same as that of Experiment 1, except for the following differences (see Figure 2): (1) the intra-dimension, *shape*-distractor conditions (TD-Shape, and DO-Shape) were omitted; (2) a pure target-distractor-absent condition (TD-Absent) was added; and (3) all six (randomly intermixed) conditions were each repeated 100 times, yielding a total of 600 trials performed in 10 blocks.

Experiment 2b introduced the following changes: (1) the non-target items (other than the salient distractor) were blue triangles, instead of the blue circles in Experiment 1; (2) the intra-dimension (shape) distractor was a blue *circle*, featurally dissimilar to the blue square target in Experiment 1; (3) a target-distractor-absent condition was added; and (4) there were 100 (randomly intermixed) trials per each of the eight conditions, that is, 800 trials in total presented in 10 blocks.

3.2 | Results

Figure 3b,c show the mean RTs and error rates for Experiments 2a and 2b, respectively. The outcome of two-way repeated-measures ANOVAs with the factors Target and Distractor Type for RTs and Error rates are summarized in Table 1. With the target prevalence of 50%, error rates were comparable between the target-present and -absent conditions, as well as among the different Distractor-Type conditions in both Experiments 2a and 2b. In Experiment 2b, the Distractor Type × Target interaction was significant, but the post hoc comparisons revealed no significant differences ($ps > .174$). Overall, the non-significant Target effects suggest that balancing the ratio of target-present to target-absent trials in Experiments 2a and 2b removed the bias, evident in Experiment 1, to respond positively (i.e., produce an increased false-alarm rate) on target-absent trials.

Importantly, the pattern of RT effects in Experiments 2a and 2b resemble the pattern obtained in Experiment 1 (Figure 3). In particular, a significant slowing of RT was evident only when an intra-dimension, shape-defined distractor was present in the display, while RT performance was comparably uninfluenced by the presence of a cross-dimension, color-defined distractor or a cross-modality, vibrotactile distractor.

Specifically, in Experiment 2a, in which the intra-dimension Shape distractor was omitted, both main effects (Target, and Distractor Type) were significant, and the Distractor-Type × Target interaction was non-significant (Table 1). RTs were by some 20 ms faster when a target was present versus absent, exhibiting the typical Target effect. Further, RTs were somewhat slowed (12 ms, $p < .01$) by the presence versus absence of a distractor (either a Color or a Vibration singleton), without a difference between the two distractor types ($p = .748$).

In contrast, Experiment 2b showed a different pattern compared to Experiment 2a when the Shape distractor within the same dimension was included (Figure 3c). The Target effect increased to 32 ms ($p = .002$). And compared to the distractor-absent condition, the shape distractor greatly slowed down responding, by 46 ms ($p < .001$), whereas the presence of a color (7 ms) or vibrotactile (8 ms) distractor had no significant impact ($ps > .09$). Thus, the significant Distractor Type × Target interaction was mainly caused by the intra-dimension Distractor condition.

A further analysis of singleton eccentricity effects (Appendix S3) revealed essentially a similar pattern to that seen in Experiment 1: there was an eccentricity effect only on target-present (i.e., TO) trials, but not on target-absent (i.e., DO) trials, with the RTs for the fastest distractor-only conditions (DO-Color and DO-Vibration) being similar to the slowest condition in the target-only condition (Figure S3). This indicates that participants tended to respond "target-absent" only after sufficient time had elapsed to allow even the "slowest target" (had it been present) to be registered, in order to avoid missing a target. Again, as in Experiment 1, the intra-dimension DO-Shape distractor (in Experiment 2b) induced a large additive RT cost relative to the DO-Color and DO-Vibration distractors, reflecting the additional waiting time required to allow a Shape target to be registered in the presence of a competing Shape distractor.

Further cross-experiment comparisons of the baseline distractor-absent conditions (including that in Experiment 1) revealed the baseline RTs to differ significantly among Experiments, $F(2, 55) = 5.83$, $p = .005$, $\eta_p^2 = 0.175$. Responding was generally faster in Experiment 1 versus Experiment 2b (81 ms, $p = .004$), but not compared to Experiments 2a (difference = 26 ms, $p = .85$) or between Experiments 2a and 2b (difference = 55 ms, $p = .1$), likely attributable to the higher target prevalence in Experiment 1.

3.3 | Discussion

Experiment 2 replicated the pattern of distractor-interference pattern seen in Experiment 1: strong interference occurred only when an intra-dimension distractor was present, despite the intra-dimension (circle) distractor sharing no common features with the square target; in contrast, there was no (Experiment 2b) or a minor interference (Experiment 2a) with cross-dimension and cross-modality distractors. This suggests that the strong distractor interference resulting from the intra-dimension distractor cannot be explained by target-distractor similarity in the shape dimension. By implication, it is more likely that participants performed the task in singleton-detection mode, and less likely that they operated in feature-search mode.

While an account of the selective interference by shape distractors in search for a shape target in terms of "feature-search" may be hard to rule out definitely, it is not immediately clear why a feature-search mode as such would eliminate the interference from cross-dimension and cross-modality distractors.[8] When considered in terms of a Guided-Search-type architecture of attentional priority computation and selection, "feature search" would mean the adoption of a strong top-down (template-based) enhancement of critical target features at the early, feature-coding level. In the bottom-up chain of priority computation, this would increase the feature-contrast signals generated by the target, giving them an edge in the competition for selection. It is not clear, however, why this would effectively prevent, say, irrelevant color signals from causing interference when searching for a shape feature target. Within the framework of the DWA (Found & Müller, 1996; Liesefeld & Müller, 2019; Müller et al., 1995), the reason is the reduction of the integration weights (at the priority-map level) of any feature-contrast signals emerging in the color dimension – and this down-weighting (in the computation of priority signals) is separate from any top-down up-weighting of critical target features in entry-level feature coding.

Consistent with this notion is a pattern of findings reported by Zehetleitner et al. (2012). In one task condition, Zehetleitner et al. induced observers to operate a shape-feature search mode in phase 1 of the search task by making the display items shape-heterogenous (in the other condition, participants were induced to operate a singleton-detection mode). This was then followed by a second, test phase in which the shape target was a singleton presented among homogeneous non-target shapes. According to Leber and Egeth (2006a, 2006b), observers persist with the originally induced task set even though, in principle, either feature-search or singleton-detection mode would be feasible in phase 2. What Zehetleitner et al. (2012) found (in their Experiment 2) was that when a color distractor was introduced only in phase 2 (after observers had never encountered a distractor in phase 1), it caused significant interference even though observers could be assumed to still operate in feature-search mode (the interference effect was almost as marked as when observers had been induced to operate a singleton-detection mode in phase 1). Interference, in the feature-mode induction group, was reduced to non-significant levels (in both phase 1 and phase 2) only when observers were presented – and so had to learn to deal – with color distractors already in phase 1 (Experiment 1). This argues that the feature-search mode as such does not prevent interference from cross-dimension distractors; rather observers have to additionally develop some special strategy that mitigates the intrusion of such distractors into the search – such as "dimension weighting."

Interestingly in this context, when an intra-dimension distractor (shape) could occur (in Experiment 2b), interference by cross-dimension and cross-modality distractors was effectively reduced to the baseline level (indicative of near-perfect dimension/modality-based distractor filtering). In contrast, when there was no intra-dimension distractor (in Experiment 2a), cross-dimension and cross-modality distractors produced a modest interference effect of some 12 ms. Assuming that this is a reliable (i.e., in future work replicable) difference, it points to the presence of intra-dimension distractors influencing the degree to which distractor signals are down-weighted in non-target dimensions or modalities, perhaps because the possible presence (strongly interfering) intra-dimension distractors makes participants engage a greater degree of executive control generally (cf. Zehetleitner et al., 2012).

In any case, based on our behavioral control experiments (Experiments 2a and 2b), the results of Experiment 1 are difficult to explain in terms of a "feature-similarity" or "search-mode" account, and instead they are more consistent with dimension- and, respectively, modality-based distractor shielding.

4 | GENERAL DISCUSSION

This present study was designed to compare and contrast the interference effects of three types of salient distractor in a shape-search scenario. The behavioral results revealed the presence of an intra-dimension (shape) distractor to cause strong RT interference, whereas cross-dimension (color) and cross-modality (vibrotactile) distractors interfered only little (if at all). Electrophysiologically, the presence of an intra-dimension distractor competing with the target reduced the target-referenced N2pc, CDA, and cCDA, whereas these ERLs were not significantly impacted by competing cross-dimension and cross-modality distractors. On

[8]This would also apply to an alternative account suggested to us by an anonymous reviewer, namely, that "attentional guidance might use a "quick and dirty" guidance process to first get attention to items that are "good enough," followed by a more precise target template to select the target item (cf. Yu et al., 2022). In the current context, individuals might search for "shape-like stimuli, then restrict search to the "square," while color and vibration provide minimal information concerning the target" (personal communication, March 16, 2023). While such a two-stage process this conceivable, two questions remain: The first is why attentional guidance would be, or have to be, set to any odd-one-out shape generally in the first stage when the shape target shows minimal or no feature overlap with the shape distractor (as in Experiment 1 and, especially, in Experiment 2b)? And, second, if specific-feature guidance is not possible at this stage, then how is guidance actually set to prioritize odd-one-out shape items generally, and not odd-one-out color and vibration items, unless one assumes that signals in these dimensions/modalities are differentially weighted?

target-absent trials (in which distractor appeared on their own), the intra-dimension (shape) distractor elicited a distractor-referenced N2pc and a cCDA – a pattern not seen with the cross-dimension and cross-modality distractors. Together, these component differences indicate that, in contrast to the color and vibration distractors, the shape distractor could not be effectively kept out of the search – and, on distractor-only trials, it may even have been processed up to the level of response selection (as suggested by the cCDA).

The vibrotactile distractor presented alone (DO condition) elicited a robust CCN that appeared to propagate to the occipital region, where it induced a numerical N2pc. Such a signal propagation was also evident on the target-present trials: a significantly CCP (a component equivalent to CCN in the target-absent condition) propagated to the occipital region reducing the target-referenced N2pc.

Although visual – Color and Shape – distractors elicited an early positivity (Ppc) on DO trials, this was comparable to the positivity elicited by the target on TO trials. This makes it unlikely that the early positivities on DO-Color and DO-Shape trials reflect a specifically distractor-related process. Instead, these positivities (including that elicited by the target) are more consistent with early "attend-to-me" signaling (Jannati et al., 2013; McDonald et al., 2023) by any odd-one-out stimulus in the display (whether target or distractor).

Overall, this pattern of results is in accord with the dimension- and modality-weighting accounts proposed by Müller and, respectively, Töllner and colleagues (Found & Müller, 1996; Liesefeld & Müller, 2019; Müller et al., 1995; Töllner et al., 2009). The intra-dimension shape distractor was handled least efficiently because its feature-contrast signal could not be selectively down-weighted without impacting the attentional priority of the shape-defined target. In contrast, it was possible to down-weight the non-target-dimension (color), which led to almost perfect performance when the distractor was color. The same was true for distractors defined in a different (the vibrotactile) modality. The vibrotactile distractor did cause some interference on target-absent trials, but this may have been because the task required searching for a *visual* target and vibrotactile distractors were relatively rare compared to visual distractors.

4.1 | Dimension-based distractor handling

In the present study, the target-defining feature, a *square* shape, was known in advance. So, in principle, participants could use a *feature-template*-based strategy (Bacon & Egeth, 1994; Duncan & Humphreys, 1992; Folk et al., 1992; Wolfe & Horowitz, 2004) to top-down bias search toward the task-relevant features defining the *square*. If participants strictly operated such a feature-based top-down set, irrelevant ("triangle," "magenta," and "high-frequency vibration") features should have *all* been effectively kept out of the search, predicting little difference among the different types of distractor. In theory, this would also have been the "optimal" strategy, given that the target never changed while the salient distractor was variable across trials. Yet, only intra-dimension, but not a cross-dimension or cross-modality, distractors interfered with detection of the shape-defined target, even when the feature overlap of the shape distractor with shape target was minimized in Experiment 2b. We take this to indicate that other mechanisms, in addition to any top-down feature-based biasing, must have come into play (potentially over and above any target-feature-based biasing), in particular: dimension- and modality-based distractor-shielding mechanisms.

According to the dimension-weighting account (DWA, Found & Müller, 1996; Liesefeld & Müller, 2019) – essentially a specification of the standard architecture of priority computation for search guidance – it is not possible to set oneself for, or selectively "up-weight," a specific target-defining feature (e.g., Square) without "up-weighting" the encompassing feature dimension (in the example, Shape/Form[9]). Accordingly, any feature-contrast signals within the target-defining dimension would be up-weighted in the computation of attentional priority – which is why a shape distractor (such as a Triangle) is a strong competitor for the allocation of attention. Further, according to the DWA, feature-contrast signals generated in other, task-irrelevant dimensions can be down-weighted – which is why a distractor singled out in a non-target-defining dimension (such as Color) can be effectively kept out of the competition for selection.

One critical prediction of the DWA and, respectively, its extension to an MWA is that dimension/modality-based distractor suppression works only with cross-dimension/modality distractors, but not intra-dimension distractors (Liesefeld & Müller, 2019; Müller et al., 1995; Zhang et al., 2019) – a pattern confirmed

[9]Whether "Shape/Form" constitutes a unitary "dimension" is questionable, given the many different types of shape features that are coded in early vision and are detected efficiently (including line junctions, including triple line junctions that the visual system interprets in terms of 3D shape; e.g., Enns & Rensink, 1990). This is why, in other work, we have referred to Shape/Form as a "domain" rather than a basic "dimension." The only basic shape dimension that we used relatively systematically in previous DWA-related work is line "orientation" (e.g., Found & Müller, 1996).

by our behavioral findings. Electrophysiologically, this pattern was mirrored in the early attention-allocation index N2pc: the target-elicited N2pc was prominent in the target-only (TO) condition, but significantly reduced when an intra-dimension (Shape) distractor competed with the target for the allocation of attention (TD-shape condition).

One consequence of the down-weighting of distractor signals is that they would engage attention generally less, regardless of whether or not a target is present in the display. To test this hypothesis, we compared the sum of the target-distractor (TD) and the distractor-only (DO) ERLs (owing to their opposite subtractions) to the Target-only (TO) ERL. We hypothesized that if attentional engagement by the distractor is similar in the target-present and -absent conditions, the summed ERLs should be near-equal to the "fully-engaged" TO ERL, by "restoring" the attentional resources allocated to the distractor back to the target. This turned out to be true for the early N2pc component (see Appendix S4). Together with the analysis of the timing and amplitude of the N2pc on fast- versus slow-RT trials (see Section 2.2.2), this suggests that the shape target and shape distractor engaged attention in near-equal portions on TD-Shape trials. In contrast, the target-elicited N2pc remained (nearly) unaffected when a cross-dimension (TD-Color) distractor appeared on the side opposite to the target, and cross-dimension (DO-Color) distractors presented alone failed to induce any significant N2pc. Also, no P_D was observed for cross-dimension and cross-modality distractors. These patterns suggest that such distractors did not engage attention and so did not need to be reactively suppressed.

The pattern of CDA effects mirrored that of the N2pc effects. In search tasks, the CDA can be taken to be indicative of post-selective item processing in (visual) working memory, that is, of the working-memory resources available to be committed to processing selected items in order to accomplish the task at hand (Chen et al., 2022; Töllner et al., 2014, 2015; Wiegand et al., 2014; Zinchenko et al., 2020). As indicated by the N2pc effects, the intra-dimensional distractor engaged attention. That is, in the TD-Shape condition, it was selected along with the target (evidenced by the reduced target-referenced N2pc amplitude compared to the TO condition), drawing processing resources away from the target at the post-selective stage – the latter being reflected in the target-related CDA being reduced in the TD-Shape compared to the target-only (TO) condition. This pattern of CDA effects was seen for both electrode pair PO7/PO8 and, in particular, pair C3/C4 (i.e., the cCDA). In contrast, with TD-Color and TD-Vibration distractors competing with the target, the CDA and cCDA remained the same as in the TO baseline, indicative of uncompromised post-selective processing of the shape *target* – because color and vibro-tactile distractors were not attentionally selected (evidenced by the undiminished target-referenced N2pcs in the TD-Color and TD-Vibration conditions).

This pattern of behavioral and electrophysiological results is generally in line with the DWA and its extension, the MWA.

4.2 | Cross-modal distractor handling

The modality-weighting account (MWA, Töllner et al., 2009) provides a simple extension of the dimension-weighting account (DWA) to multi-modal search scenarios, by assuming an additional "modality" layer (above a "dimension" layer) in priority computation. This would allow the search-guidance system to effectively down-weight any feature-contrast signals generated by distractors in a non-target-defining modality (similar to signals in an irrelevant dimension within the target-defining modality), which is consistent with the behavioral data.

Interestingly, while the vibro-tactile distractor could be prevented from generating interference as well as the color distractor, electrophysiologically, it elicited a strong early CCN/CCP component in the sensorimotor region (C3/C4) on both target-present and -absent trials, indicative of the registration of the tactile singleton by the system on both types of trial (recall that CCN is reversed in polarity to CCP because, in the target-absent conditions, the reference is the distractor, rather than the target, location). In the presence of a competing target (TD-Vibration condition), the vibro-tactile distractor significantly reduced the amplitude of the target-referenced N2pc relative to the target-only (TO) condition. While this reduction resembles that caused by the Shape distractor (TD-Shape condition), it is likely owing to the spreading of CCP-related activity from the sensorimotor (C3/C4) to the posterior (PO7/8) region, where it masks the target-elicited N2pc (though we cannot rule out a reduction of target-elicited N2pc per se). This would imply that the distractor-elicited CCP reflects more the sensory registration of an odd-one-out touch signal in the sensorimotor region than the engagement of attention (the latter should have adversely impacted detection of the shape target).

In any case, the lack of behavioral interference from our cross-modality, vibro-tactile distractors is consistent with a recent report by Mandal and Liesefeld (2022) that spatially localized *auditory* distractors failed to interfere with visual search for a *shape*-defined target. Even though space coding works fundamentally differently with auditory and somatosensory stimuli, in terms of the MWA these convergent findings would suggest that it is generally possible to keep distractors defined in irrelevant modalities out of attentional-priority computations. Note, however, that these findings do not argue strongly in favor of the extra, modality-specific level in the architecture of priority computation that is envisaged by the MWA: they might also be explained by a flatter, DWA-based architecture that assumes signal integration across a set of hierarchically equivalent "dimensions." Further evidence would be needed to support the postulation of a modality-specific level, such as the gains produced by targets redundantly defined in different modalities (e.g., popping out by both shape and vibro-tactile feature contrast) exceeding those of targets redundantly defined within one modality (popping out by both shape and color contrast, see Nasemann et al., 2023).

4.3 | Implications for the "attentional-capture, rapid-disengagement" and "signal-suppression" accounts

Our findings cannot be easily squared with the idea that salient distractors invariably capture attention, upon which control is then exercised reactively, by rapid disengagement of attention from the distractor and re-orientation to the target (Theeuwes, 2010, 2021). Of note, however, our distractors were equally (bottom-up) salient to the target, rather than more salient. Accordingly, according to a "probabilistic-capture" model (cf. Zehetleitner et al., 2013), one would not have expected the distractors to capture attention on all or the majority of trials, but rather only on a fraction closer to 50%. Also, in the early studies supporting pure saliency-driven attentional capture by color-defined distractors in search for a shape-defined target (Theeuwes, 1992, 2013), the non-distractor (i.e., target plus non-target) and distractor colors as well as the target and non-target (i.e., non-target plus distractor) shapes were randomly swapped across trials, which may have fostered a pure "singleton-detection" search mode (cf. Bacon & Egeth, 1994; Chang & Egeth, 2019; Gaspelin et al., 2015; Gaspelin & Luck, 2018a). In the present study, by contrast, the target shape (and color) were completely predictable, as were the distractor features – in principle allowing participants to top-down bias search toward the critical target feature by setting up a positive (square-shape) target template, as well as against distractor features by setting up negative (triangle-shape, magenta-color, and 100-frequency tactile vibration) distractor templates. Although a feature-based search mode was thus possible, the fact that participants failed keep the Shape distractor out of the search would suggest that either they did not adopt such a search mode, or that – contrary to the notion of feature-based biasing of search (e.g., Bacon & Egeth, 1994; Chang & Egeth, 2019; Gaspelin et al., 2015; Gaspelin & Luck, 2018b) – this mode was not effective in dealing with intra-dimension distractors (even when they were made maximally separable from the target in Experiment 2b).

Nevertheless, by permitting search to be feature-driven in principle, the present conditions may have been non-optimal to test a strong "attentional-capture, rapid-disengagement" account. However, this account would find it hard to explain why only the shape distractor caused significant interference (relative to the target-only baseline) at both the behavioral and electrophysiological levels, but not the color and vibro-tactile distractors, even though the distractors were equated for bottom-up salience.[10] Further, even when the Shape distractor engaged attention, we found no electrophysiological evidence of a reactive suppression process, in particular: while the Shape distractor generated an N2pc (as can be inferred from the greatly diminished target-elicited N2pc on trials with a Shape distractor on the opposite side [TD-Shape trials]), this was not followed by a P_D – a temporal sequence shown by Liesefeld et al. (2017) to be diagnostic of post-capture distractor suppression to enable re-allocation of attention to the target location (in a similar, "shape-target, shape-distractor" search scenario; the present study; see also, e.g., Gaspar & McDonald, 2014), who found a robust P_D in a "color-target, color-distractor" search task when the distractor was highly salient). Instead, the Shape distractor appeared to be processed in parallel with the target at the post-selective stage, that is, both were represented in vWM and perhaps compared in parallel to the target template (as evidenced by the reduced target-elicited CDA on TD-Shape trials). Possibly, though, the lack of a reactive, post-capture P_D may be owing to the limited, 250-ms exposure duration of the search displays in the present study, which may have forced participants to adopt a parallel, rather than a serial, attention-allocation strategy (Eimer & Grubert, 2014).

[10] Concerning the lack of an N2pc elicited by Color distractors, one attempt to explain this would be by assuming that attention was "shifted" to the Color distractor, but not "engaged" by it – permitting attention to be rapidly re-oriented to the target on TD trials. While this could "rescue" the rapid-disengagement account, this explanation is virtually impossible to rule out (as, e.g., noted by Luck et al., 2021) and not compatible with the original rapid-disengagement account.

Thus, even though our conditions may have been non-optimal for a strong test of the "attentional-capture, rapid-disengagement" account, both the behavioral and the electrophysiological results are at odds with it.

The same appears to apply to the "signal-suppression hypothesis" (Gaspelin et al., 2015; Gaspelin & Luck, 2018a, 2018c). To explain the behavioral data, this account would have to assume that color and vibration distractors could be successfully suppressed proactively (perhaps by setting up negative templates for the respective color and vibrotactile features), but not shape distractors. But then, proponents of this account would have to explain why it was not possible to suppress the latter type of distractor. For instance, why was it not possible to set up a negative template for "triangle" shapes, even though triangles are separable from squares based on possessing unique (oblique) side orientations (Buetti et al., 2019; Grüner et al., 2021; Wolfe & Horowitz, 2004, 2017; Xu et al., 2021). A likely explanation would have to involve assumptions similar to those central to the DWA/MWA, namely: the handling of intra-dimensional distractors is inherently more difficult than the handling of cross-dimension or cross-modal distractors. Of course, studies designed to test the signal-suppression hypothesis have typically used a (featurally, or at least dimensionally) fixed distractor type, rather than, as here, randomizing the distractor types across trials – and perhaps there is limit to the number of different distractors than can be effectively handled (e.g., maintaining three, rather than just one or two, distractor templates may just not be possible). Thus, when confronted with too many distractor types, one has to select one or two – and, for some structural reasons, the Shape distractor was not among those selected in the present study. This would go some way to account for our results. However, even in the two conditions in which the distractor could be effectively kept out of the search (evidenced by undiminished target-elicited N2pc amplitudes compared to the TO baseline), there was no evidence of an early, distractor-specific P_D component,[11] that is: successful proactive distractor suppression was not associated with an ERP signature assumed, by the signal-suppression hypothesis, to reflect the active prevention of the (mis-)allocation of attention to the distractor. We take this to suggest that no process potentially reflected in the P_D is strictly necessary for successful *pro-active* distractor handling.

[11]Recall that, although we found an early positivity, this was not specifically related to the visual distractor: it was seen not only on DO-Shape and DO-Color trials, but also (and if, anything more prominently) on TO trials. Given this, it is unlikely to reflect a suppressive mechanism (unless one assumes that the target was suppressed, too).

This is consistent with the DWA/MWA, which explain *pro-active* distractor suppression in terms of the *tonic* down-weighting of feature-contrast signals in task-irrelevant dimensions/modalities. As the weight settings persist across trials, any distractor signals are attenuated at the dimension or, respectively, modality levels wherever they arise in the display (i.e., the attenuation works in a spatially global, rather than location-specific, manner), and the weight settings should be effective even in the absence of a search display (for neurophysiological evidence of target-dimension weighting in the absence of a stimulus, operating even prior to stimulus presentation, see, e.g., Schledde et al., 2017). As a result, they are not passed, or passed only in weakened form (e.g., Experiment 2a), to the cross-dimensional/−modal saliency-summation stage: the attentional priority map. Thus, pro-active suppression occurs by "passive" global filtering of distractor signals, and no "active," location-specific suppression process needs to come into play to prevent an impending mis-allocation of attention to the distractor.

Of course, the present finding of effective pro-active suppression of cross-dimensional/−modal distractors does not exclude the possibility of (probabilistic) attentional capture by cross-dimension/−modality distractors under other stimulus conditions, especially when the distractors are more salient than the target (see, e.g., Sauter et al., 2021, for evidence from oculomotor capture), instead of being equally salient, as in the present study. The pattern of behavioral interference and P_D effects reported by Gaspar and McDonald (2014) would be in line with this: As already outlined in the Introduction, they found a more salient distractor defined within the same (color) dimension as the target to elicit a robust P_D (Experiment 1), but not a less salient distractor (Experiment 3). In search for a shape target, a cross-dimension, color distractor (the same stimulus as in Experiment 1) also elicited a small yet significant P_D (Experiment 2). In light of the present findings, we take this pattern to suggest that a P_D may be observed even with cross-dimension (or cross-modality) distractors if they are sufficiently salient to survive dimension- (or modality-) based down-weighting. As, for instance, Müller et al. (2010) have argued, the (multiplicative) integration weights assigned to the feature-contrast signals within a given dimension must be larger than zero, to ensure that potentially survival-relevant odd-one-out stimuli in a currently task-irrelevant dimension can interrupt ongoing processing and take control of action. Given this, there is a greater-than-zero probability that even relatively non-salient distractors will be selected first and need to be re-actively suppressed for attention to be re-oriented to the target.

A different notion of proactive suppression to that assumed by the DWA/MWA appears to be implied in the "signal-suppression hypothesis." According to this account, distractors generate an "attend-to-me" signal, but the deployment of attention to the distractor location is prevented (or lessened) by the active intervention of some phasic, distractor-location-specific control process reflected in the Ppc. So, even though the process is *pro*-active, in the sense that it is set up in advance (perhaps driven by some distractor template maintained in working memory), it is *re*-active in the sense that it comes into play only once a distractor signal has been registered. In contrast, dimension/modality weighting is designed to prevent the "attend-to-me" signal of the distractor signal in the first instance. Thus, it remains that distractor suppression sometimes involves processes reflected in a P_D (e.g., Gaspelin & Luck, 2018c; Luck et al., 2021), and sometimes processes that do not involve a P_D (e.g., Gaspar & McDonald, 2014; van Moorselaar & Slagter, 2019; present study). Given this, further work is needed to delineate the conditions under which distractor suppression works in one or the other mode.

4.4 | Conclusion

Using a multi-modal display design, the present study investigated the handling of salient but task-irrelevant distractors in a visual search task requiring detection of a shape-defined target. Three types (of bottom-up equally salient) of distractor were compared: a distractor defined within the same visual dimension as the target (Shape), a distractor defined in a different visual dimension (Color), and a distractor defined in a different modality (tactile Vibration frequency). We found only the intra-dimensional (Shape) distractor to generate significant behavioral interference (even when it was featurally maximally dissimilar to the target), which went along with reduced target-elicited N2pc and CDA components. In contrast, these components were relatively intact in the presence of Color or Vibration distractors (with neither of these irrelevant pop-out stimuli being associated with an early, specifically distractor-related P_D). The vibrotactile distractor was registered by the somatosensory system (evidenced by prominent CCN/CCP components), but, like the color distractor, did not appear to engage attention (reflected in the N2pc) and impact post-selective target-identification and response-selection processes (reflected in the CDA). We take this pattern of behavioral and electrophysiological effects to reflect constraints inherent in the computation of attentional priorities: only cross-dimension/−modality distractors, but not intra-dimension distractors, may be effectively filtered out by down-weighting their signals at the saliency-integration stage, the search-guiding priority map.

AUTHOR CONTRIBUTIONS

Shao-Yang Tsai: Conceptualization; data curation; formal analysis; methodology; project administration; resources; software; visualization; writing – original draft. **Jan Nasemann:** Conceptualization; methodology; project administration; software; validation; writing – review and editing. **Nan Qiu:** Resources; validation; writing – review and editing. **Thomas Töllner:** Conceptualization; funding acquisition; investigation; methodology; resources; supervision. **Hermann J. Müller:** Conceptualization; funding acquisition; resources; supervision; writing – review and editing. **Zhuanghua Shi:** Conceptualization; formal analysis; funding acquisition; project administration; resources; software; supervision; validation; visualization; writing – review and editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Allenmark, F., Zhang, B., Liesefeld, H. R., Shi, Z., & Müller, H. J. (2019). Probability cueing of singleton-distractor regions in visual search: The locus of spatial distractor suppression is determined by colour swapping. *Visual Cognition*, *27*(5–8), 576–594. https://doi.org/10.1080/13506285.2019.1666953

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496. https://doi.org/10.3758/bf03205306

Becker, S. I., Folk, C. L., & Remington, R. W. (2010). The role of relational information in contingent capture. *Journal of Experimental Psychology. Human Perception and Performance*, *36*(6), 1460–1476. https://doi.org/10.1037/a0020370

Bell, A. J., & Sejnowski, T. J. (1995). An information-maximization approach to blind separation and blind deconvolution. *Neural Computation*, *7*(6), 1129–1159. https://doi.org/10.1162/neco.1995.7.6.1129

Buetti, S., Xu, J., & Lleras, A. (2019). Predicting how color and shape combine in the human visual system to direct attention. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-56238-9

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*(4), 523–547. https://doi.org/10.1037/0033-295x.97.4.523

Chang, S., & Egeth, H. E. (2019). Enhancement and suppression flexibly guide attention. *Psychological Science*, *30*(12), 1724–1732. https://doi.org/10.1177/0956797619878813

Chen, S., Shi, Z., Zinchenko, A., Müller, H. J., & Geyer, T. (2022). Cross-modal contextual memory guides selective attention in visual-search tasks. *Psychophysiology*, *e14025*, e14025. https://doi.org/10.1111/psyp.14025

Chun, M. M., & Wolfe, J. M. (1996). Just say No: How are visual searches terminated when there is No target present? *Cognitive Psychology*, *30*(1), 39–78. https://doi.org/10.1006/cogp.1996.0002

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dodwell, G., Liesefeld, H. R., Conci, M., Müller, H. J., & Töllner, T. (2021). EEG evidence for enhanced attentional performance during moderate-intensity exercise. *Psychophysiology*, *58*(12), e13923. https://doi.org/10.1111/psyp.13923

Duncan, J., & Humphreys, G. (1992). Beyond the search surface: Visual search and attentional engagement [Review of *Beyond the search surface: Visual search and attentional engagement*]. *Journal of Experimental Psychology. Human Perception and Performance*, *18*(2), 578–588; discussion 589–593. https://doi.org/10.1037//0096-1523.18.2.578

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*(3), 225–234. https://doi.org/10.1016/0013-4694(96)95711-9

Eimer, M., & Driver, J. (2000). An event-related brain potential study of cross-modal links in spatial attention between vision and touch. *Psychophysiology*, *37*(5), 697–705. https://www.ncbi.nlm.nih.gov/pubmed/11037046

Eimer, M., Forster, B., Fieger, A., & Harbich, S. (2004). Effects of hand posture on preparatory control processes and sensory modulations in tactile-spatial attention. *Clinical Neurophysiology*, *115*(3), 596–608. https://doi.org/10.1016/j.clinph.2003.10.015

Eimer, M., & Grubert, A. (2014). Spatial attention can Be allocated rapidly and in parallel to new visual objects. *Current Biology: CB*, *24*(2), 193–198. https://doi.org/10.1016/j.cub.2013.12.001

Enns, J. T., & Rensink, R. A. (1990). Sensitivity to three-dimensional orientation in visual search. *Psychological Science*, *1*(5), 323–326. http://pss.sagepub.com/content/1/5/323.short

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/bf03193146

Feldmann-Wüstefeld, T., & Schubö, A. (2013). Context homogeneity facilitates both distractor inhibition and target enhancement. *Journal of Vision*, *13*(3), 11. https://doi.org/10.1167/13.3.11

Feldmann-Wüstefeld, T., Uengoer, M., & Schubö, A. (2015). You see what you have learned. Evidence for an interrelation of associative learning and visual selective attention. *Psychophysiology*, *52*(11), 1483–1497. https://doi.org/10.1111/psyp.12514

Ferrante, O., Patacca, A., Di Caro, V., Della Libera, C., Santandrea, E., & Chelazzi, L. (2018). Altering spatial priority maps via statistical learning of target selection and distractor filtering. *Cortex*, *102*, 67–95. https://doi.org/10.1016/j.cortex.2017.09.027

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology. Human Perception and Performance*, *18*(4), 1030–1044. https://doi.org/10.1037//0096-1523.18.4.1030

Forster, B., Tziraki, M., & Jones, A. (2016). The attentive homunculus: ERP evidence for somatotopic allocation of attention in tactile search. *Neuropsychologia*, *84*, 158–166. https://doi.org/10.1016/j.neuropsychologia.2016.02.009

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a “dimension-weighting” account. *Perception & Psychophysics*, *58*(1), 88–101. https://doi.org/10.3758/bf03205479

Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *34*(16), 5658–5666. https://doi.org/10.1523/JNEUROSCI.4161-13.2014

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2015). Direct evidence for active suppression of salient-but-irrelevant sensory inputs. *Psychological Science*, *26*(11), 1740–1750. https://doi.org/10.1177/0956797615597913

Gaspelin, N., Leonard, C. J., & Luck, S. J. (2017). Suppression of overt attentional capture by salient-but-irrelevant color singletons. *Attention, Perception & Psychophysics*, *79*(1), 45–62. https://doi.org/10.3758/s13414-016-1209-1

Gaspelin, N., & Luck, S. J. (2018a). The role of inhibition in avoiding distraction by salient stimuli. *Trends in Cognitive Sciences*, *22*(1), 79–92. https://doi.org/10.1016/j.tics.2017.11.001

Gaspelin, N., & Luck, S. J. (2018b). Distinguishing among potential mechanisms of singleton suppression. *Journal of Experimental Psychology. Human Perception and Performance*, *44*(4), 626–644. https://doi.org/10.1037/xhp0000484

Gaspelin, N., & Luck, S. J. (2018c). Combined electrophysiological and behavioral evidence for the suppression of salient distractors. *Journal of Cognitive Neuroscience*, *30*(9), 1265–1280. https://doi.org/10.1162/jocn_a_01279

Geyer, T., Müller, H. J., & Krummenacher, J. (2008). Expectancies modulate attentional capture by salient color singletons. *Vision Research*, *48*(11), 1315–1326. https://doi.org/10.1016/j.visres.2008.02.006

Goschy, H., Bakos, S., Müller, H. J., & Zehetleitner, M. (2014). Probability cueing of distractor locations: Both intertrial facilitation and statistical learning mediate interference reduction. *Frontiers in Psychology*, *5*, 1195. https://doi.org/10.3389/fpsyg.2014.01195

Grüner, M., Goller, F., & Ansorge, U. (2021). Simple shapes guide visual attention based on their global outline or global orientation contingent on search goals. *Journal of Experimental Psychology. Human Perception and Performance*, *47*(11), 1493–1515. https://doi.org/10.1037/xhp0000955

Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience*, *21*(4), 760–775. https://doi.org/10.1162/jocn.2009.21039

Hilimire, M. R., & Corballis, P. M. (2014). Event-related potentials reveal the effect of prior knowledge on competition for representation and attentional capture. *Psychophysiology*, *51*(1), 22–35. https://doi.org/10.1111/psyp.12154

Ipata, A. E., Gee, A. L., Gottlieb, J., Bisley, J. W., & Goldberg, M. E. (2006). LIP responses to a popout stimulus are reduced if it is overtly ignored. *Nature Neuroscience*, *9*(8), 1071–1076. https://doi.org/10.1038/nn1734

Jannati, A., Gaspar, J. M., & McDonald, J. J. (2013). Tracking target and distractor processing in fixed-feature visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(6), 1713–1730. https://doi.org/10.1037/a0032251

Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception ECVP Abstract Supplement*, *36*, 14.

Krummenacher, J., Müller, H. J., & Heller, D. (2001). Visual search for dimensionally redundant pop-out targets: Evidence for parallel-coactive processing of dimensions. *Perception & Psychophysics*, *63*(5), 901–917. https://www.ncbi.nlm.nih.gov/pubmed/11521855

Krummenacher, J., Müller, H. J., & Heller, D. (2002). Visual search for dimensionally redundant pop-out targets: Parallel-coactive processing of dimensions is location specific. *Journal of Experimental Psychology. Human Perception and Performance*, *28*(6), 1303–1322. https://www.ncbi.nlm.nih.gov/pubmed/12542129

Leber, A. B., & Egeth, H. E. (2006a). It's under control: Top-down search strategies can override attentional capture. *Psychonomic Bulletin & Review*, *13*(1), 132–138. https://doi.org/10.3758/bf03193824

Leber, A. B., & Egeth, H. E. (2006b). Attention on autopilot: Past experience and attentional set. *Visual Cognition*, *14*(4–8), 565–583. https://doi.org/10.1080/13506280500193438

Leblanc, E., Prime, D. J., & Jolicoeur, P. (2008). Tracking the location of visuospatial attention in a contingent capture paradigm. *Journal of Cognitive Neuroscience*, *20*(4), 657–671. https://doi.org/10.1162/jocn.2008.20051

Lee, T. W., Girolami, M., & Sejnowski, T. J. (1999). Independent component analysis using an extended infomax algorithm for mixed subgaussian and supergaussian sources. *Neural Computation*, *11*(2), 417–441. https://doi.org/10.1162/089976699300016719

Liesefeld, H. R., Liesefeld, A. M., & Müller, H. J. (2019). Distractor-interference reduction is dimensionally constrained. *Visual Cognition*, *27*(3–4), 247–259. https://doi.org/10.1080/13506285.2018.1561568

Liesefeld, H. R., Liesefeld, A. M., & Müller, H. J. (2022). Preparatory control against distraction is not feature-based. *Cerebral Cortex*, *32*(11), 2398–2411. https://doi.org/10.1093/cercor/bhab341

Liesefeld, H. R., Liesefeld, A. M., Pollmann, S., & Müller, H. J. (2019). Biasing allocations of attention via selective weighting of saliency signals: Behavioral and neuroimaging evidence for the dimension-weighting account. *Current Topics in Behavioral Neurosciences*, *41*, 87–113. https://doi.org/10.1007/7854_2018_75

Liesefeld, H. R., Liesefeld, A. M., Töllner, T., & Müller, H. J. (2017). Attentional capture in visual search: Capture and post-capture dynamics revealed by EEG. *NeuroImage*, *156*(May), 166–173. https://doi.org/10.1016/j.neuroimage.2017.05.016

Liesefeld, H. R., & Müller, H. J. (2019). Distractor handling via dimension weighting. *Current Opinion in Psychology*, *29*, 160–167. https://doi.org/10.1016/j.copsyc.2019.03.003

Liesefeld, H. R., & Müller, H. J. (2020). A theoretical attempt to revive the serial/parallel-search dichotomy. *Attention, Perception & Psychophysics*, *82*(1), 228–245. https://doi.org/10.3758/s13414-019-01819-z

Liesefeld, H. R., & Müller, H. J. (2021). Modulations of saliency signals at two hierarchical levels of priority computation revealed by spatial statistical distractor learning. *Journal of Experimental Psychology. General*, *150*(4), 710–728. https://doi.org/10.1037/xge0000970

Louie, K., Khaw, M. W., & Glimcher, P. W. (2013). Normalization is a general neural mechanism for context-dependent decision making. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(15), 6139–6144. https://doi.org/10.1073/pnas.1217854110

Luck, S. J. (2005). *An introduction to the event-related potential technique* (Vol. *66*, pp. 335–337). MIT Press. https://doi.org/10.1093/geronb/gbr025

Luck, S. J. (2011). *Electrophysiological correlates of the focusing of attention within complex visual scenes: N2pc and related ERP components*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780195374148.013.0161

Luck, S. J., Gaspelin, N., Folk, C. L., Remington, R. W., & Theeuwes, J. (2021). Progress toward resolving the attentional capture debate. *Visual Cognition*, *29*(1), 1–21. https://doi.org/10.1080/13506285.2020.1848949

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology. Human Perception and Performance*, *20*(5), 1000–1014. https://doi.org/10.1037//0096-1523.20.5.1000

Mandal, A., Liesefeld, A. M., & Liesefeld, H. R. (2022). The surprising robustness of visual attention against concurrent auditory distraction. *PsyArXiv*. https://doi.org/10.31234/osf.io/hnvdm

Mandal, A., & Liesefeld, H. R. (2022). Visual pop-out search is robust to auditory distraction. *Journal of Vision*, *22*(14), 3887. https://doi.org/10.1167/jov.22.14.3887

Mazza, V., Turatto, M., Umiltà, C., & Eimer, M. (2007). Attentional selection and identification of visual objects are reflected by distinct electrophysiological responses. *Experimental Brain Research*, *181*(3), 531–536. https://doi.org/10.1007/s00221-007-1002-4

McDonald, J. J., Gaspar, J. M., Lagroix, H. E. P., & Jolicœur, P. (2023). Difficulty suppressing visual distraction while dual tasking. *Psychonomic Bulletin & Review*, *30*(1), 224–234. https://doi.org/10.3758/s13423-022-02165-2

McDonald, J. J., Green, J. J., Jannati, A., & Di Lollo, V. (2013). On the electrophysiological evidence for the capture of visual attention. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(3), 849–860. https://doi.org/10.1037/a0030510

Müller, H. J., Geyer, T., Zehetleitner, M., & Krummenacher, J. (2009). Attentional capture by salient color singleton distractors is modulated by top-down dimensional set. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(1), 1–16. https://doi.org/10.1037/0096-1523.35.1.1

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, *57*, 1–17. https://doi.org/10.3758/BF03211845

Müller, H. J., Reimann, B., & Krummenacher, J. (2003). Visual search for singleton feature targets across dimensions: Stimulus- and expectancy-driven effects in dimensional weighting. In. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(5), 1021–1035. https://doi.org/10.1037/0096-1523.29.5.1021

Müller, H. J., Töllner, T., Zehetleitner, M., Geyer, T., Rangelov, D., & Krummenacher, J. (2010). Dimension-based attention modulates feed-forward visual processing [Review of *Dimension-based attention modulates feed-forward visual processing*]. *Acta Psychologica*, *135*(2), 117–122; discussion 133–139. https://doi.org/10.1016/j.actpsy.2010.05.004

Müller, M. M., Malinowski, P., Gruber, T., & Hillyard, S. A. (2003). Sustained division of the attentional spotlight. *Nature*, *424*(6946), 309–312. https://doi.org/10.1038/nature01812

Nasemann, J., Töllner, T., Müller, H. J., & Shi, Z. (2023). Hierarchy of intra- and Crossmodal redundancy gains in Visuo-tactile search: Evidence from the PCN. *Journal of Cognitive Neuroscience*, *in press*, *35*, 543–570.

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron*, *61*(2), 168–185. https://doi.org/10.1016/j.neuron.2009.01.002

Sauter, M., Hanning, N. M., Liesefeld, H. R., & Müller, H. J. (2021). Post-capture processes contribute to statistical learning of distractor locations in visual search. *Cortex*, *135*, 108–126. https://doi.org/10.1016/j.cortex.2020.11.016

Sauter, M., Liesefeld, H. R., Zehetleitner, M., & Müller, H. J. (2018). Region-based shielding of visual search from salient distractors: Target detection is impaired with same- but not different-dimension distractors. *Attention, Perception & Psychophysics*, *80*(3), 622–642. https://doi.org/10.3758/s13414-017-1477-4

Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. *Attention, Perception & Psychophysics*, *72*(6), 1455–1470. https://doi.org/10.3758/APP.72.6.1455

Sawaki, R., & Luck, S. J. (2014). How the brain prevents and terminates shifts of attention. In G. R. Mangun (Ed.), *Cognitive electrophysiology of attention* (pp. 16–29). Academic Press. https://doi.org/10.1016/B978-0-12-398451-7.00002-6

Schledde, B., Galashan, F. O., Przybyla, M., Kreiter, A. K., & Wegener, D. (2017). Task-specific, dimension-based attentional shaping of motion processing in monkey area MT. *Journal of Neurophysiology*, *118*(3), 1542–1555. https://doi.org/10.1152/jn.00183.2017

Stilwell, B. T., Egeth, H., & Gaspelin, N. (2022). Electrophysiological evidence for the suppression of highly salient distractors. *Journal of Cognitive Neuroscience*, *34*(5), 787–805. https://doi.org/10.1162/jocn_a_01827

Theeuwes, J. (1992). Perceptual selectivity for color and form [Review of *Perceptual selectivity for color and form*]. *Perception & Psychophysics*, *51*(6), 599–606. Springer Science and Business Media LLC. https://doi.org/10.3758/bf03211656

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, *135*(2), 77–99. https://doi.org/10.1016/j.actpsy.2010.02.006

Theeuwes, J. (2013). Feature-based attention: It is all bottom-up priming. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *368*(1628), 20130055. https://doi.org/10.1098/rstb.2013.0055

Theeuwes, J. (2021). Response to commentaries to Luck et al. (2021). Progress toward resolving the attentional capture debate. *Visual Cognition*, *29*(9), 637–643. https://doi.org/10.1080/13506285.2021.1978672

Theeuwes, J., Bogaerts, L., & van Moorselaar, D. (2022). What to expect where and when: How statistical learning drives visual selection. *Trends in Cognitive Sciences*, *26*(10), 860–872. https://doi.org/10.1016/j.tics.2022.06.001

Töllner, T., Conci, M., & Rusch, T. (2013). Selective manipulation of target identification demands in visual search: The role of stimulus contrast in CDA activations. *Journal of Vision*, *13*(3), 23. https://psycnet.apa.org/fulltext/2013-28483-001.pdf

Töllner, T., Eschmann, K. C. J., Rusch, T., & Müller, H. J. (2014). Contralateral delay activity reveals dimension-based attentional orienting to locations in visual working memory. *Attention, Perception & Psychophysics*, *76*(3), 655–662. https://doi.org/10.3758/s13414-014-0636-0

Töllner, T., Gramann, K., Müller, H. J., & Eimer, M. (2009). The anterior N1 component as an index of modality shifting. *Journal of Cognitive Neuroscience*, *21*(9), 1653–1669. https://doi.org/10.1162/jocn.2009.21108

Töllner, T., Mink, M., & Müller, H. J. (2015). Searching for targets in visual working memory: Investigating a dimensional feature bundle (DFB) model. *Annals of the new York Academy of Sciences*, *1339*(1), 32–44. https://doi.org/10.1111/nyas.12703

Töllner, T., Rangelov, D., & Müller, H. J. (2012). How the speed of motor-response decisions, but not focal-attentional selection, differs as a function of task set and target prevalence. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(28), E1990–E1999. https://doi.org/10.1073/pnas.1206382109

van Moorselaar, D., & Slagter, H. A. (2019). Learning what is irrelevant or relevant: Expectations facilitate distractor inhibition and target facilitation through distinct neural mechanisms. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *39*(35), 6953–6967. https://doi.org/10.1523/JNEUROSCI.0593-19.2019

Vatterott, D. B., & Vecera, S. P. (2012). Experience-dependent attentional tuning of distractor rejection. *Psychonomic Bulletin & Review*, *19*(5), 871–878. https://doi.org/10.3758/s13423-012-0280-4

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*(6984), 748–751. https://doi.org/10.1038/nature02447

Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Selker, R., Gronau, Q. F., Dropmann, D., Boutin, B., Meerhoff, F., Knight, P., Raj, A., van Kesteren, E. J., van Doorn, J., Šmíra, M., Epskamp, S., Etz, A., Matzke, D., … Morey, R. D. (2017). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review*, *25*, 1–19. https://doi.org/10.3758/s13423-017-1323-7

Wang, B., & Theeuwes, J. (2018). Statistical regularities modulate attentional capture independent of search strategy. *Attention, Perception & Psychophysics*, *80*(7), 1763–1774. https://doi.org/10.3758/s13414-018-1562-3

Wiegand, I., Töllner, T., Habekost, T., Dyrholm, M., Müller, H. J., & Finke, K. (2014). Distinct neural markers of TVA-based visual processing speed and short-term storage capacity parameters. *Cerebral Cortex*, *24*(8), 1967–1978. https://doi.org/10.1093/cercor/bht071

Wolfe, J. M. (2021). Guided search 6.0: An updated model of visual search. *Psychonomic Bulletin & Review*, *28*(4), 1060–1092. https://doi.org/10.3758/s13423-020-01859-9

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature*

Reviews. Neuroscience, *5*(6), 495–501. https://doi.org/10.1038/nrn1411

Wolfe, J. M., & Horowitz, T. S. (2017). Five factors that guide attention in visual search. *Nature Human Behaviour*, *1*(3), 1–8. https://doi.org/10.1038/s41562-017-0058

Won, B.-Y., Kosoyan, M., & Geng, J. J. (2019). Evidence for second-order singleton suppression based on probabilistic expectations. *Journal of Experimental Psychology. Human Perception and Performance*, *45*(1), 125–138. https://doi.org/10.1037/xhp0000594

Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, *400*(6747), 867–869. https://doi.org/10.1038/23698

Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology. Human Perception and Performance*, *29*(1), 121–138. https://doi.org/10.1037//0096-1523.29.1.121

Woodman, G. F., & Vogel, E. K. (2008). Selective storage and maintenance of an object's features in visual working memory. *Psychonomic Bulletin & Review*, *15*(1), 223–229. https://doi.org/10.3758/pbr.15.1.223

Xu, Z. J., Lleras, A., & Buetti, S. (2021). Predicting how surface texture and shape combine in the human visual system to direct attention. *Scientific Reports*, *11*(1), 6170. https://doi.org/10.1038/s41598-021-85605-8

Yu, X., Hanks, T. D., & Geng, J. J. (2022). Attentional guidance and match decisions rely on different template information during visual search. *Psychological Science*, *33*(1), 105–120. https://doi.org/10.1177/09567976211032225

Zehetleitner, M., Goschy, H., & Müller, H. J. (2012). Top-down control of attention: it's gradual, practice-dependent, and hierarchically organized. *Journal of Experimental Psychology. Human Perception and Performance*, *38*(4), 941–957. https://doi.org/10.1037/a0027629

Zehetleitner, M., Koch, A. I., Goschy, H., & Müller, H. J. (2013). Salience-based selection: Attentional capture by distractors less salient than the target. *PLoS One*, *8*(1), e52595. https://doi.org/10.1371/journal.pone.0052595

Zhang, B., Allenmark, F., Liesefeld, H. R., Shi, Z., & Müller, H. J. (2019). Probability cueing of singleton-distractor locations in visual search: Priority-map- versus dimension-based inhibition? *Journal of Experimental Psychology. Human Perception and Performance*, *45*(9), 1146–1163. https://doi.org/10.1037/xhp0000652

Zhang, B., Weidner, R., Allenmark, F., Bertleff, S., Fink, G. R., Shi, Z., & Müller, H. J. (2022). Statistical learning of frequent distractor locations in visual search involves regional signal suppression in early visual cortex. *Cerebral Cortex*, *32*, 2729–2744. https://doi.org/10.1093/cercor/bhab377

Zinchenko, A., Conci, M., Töllner, T., Müller, H. J., & Geyer, T. (2020). Automatic guidance (and misguidance) of visuospatial attention by acquired scene memory: Evidence from an N1pc polarity reversal. *Psychological Science*, *31*(12), 1531–1543. https://doi.org/10.1177/0956797620954815

Zivony, A., Allon, A. S., Luria, R., & Lamy, D. (2018). Dissociating between the N2pc and attentional shifting: An attentional blink study. *Neuropsychologia*, *121*, 153–163. https://doi.org/10.1016/j.neuropsychologia.2018.11.003

Zivony, A., & Lamy, D. (2016). Attentional capture and engagement during the attentional blink: A "camera" metaphor of attention. *Journal of Experimental Psychology. Human Perception and Performance*, *42*(11), 1886–1902. https://doi.org/10.1037/xhp0000286

Zivony, A., & Lamy, D. (2018). Contingent attentional engagement: Stimulus- and goal-driven capture have qualitatively different consequences. *Psychological Science*, *29*(12), 1930–1941. https://doi.org/10.1177/0956797618799302

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1 Pilot studies.

Appendix S2 Learning of distractor suppression.

Appendix S3 Target-distractor eccentricity and distance effects.

Appendix S4 Summation analysis.

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