The Neural Correlates of Distractor Handling in Cross-Modal Search

Shao-Yang Tsai

Graduate School of Systemic Neurosciences
LMU Munich

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Supervisors

Prof. Dr. Zhuanghua Shi

Prof. Dr. Hermann Müller

Department of Experimental Psychology

Ludwig-Maximilians-Universität München

First Reviewer:

Prof. Dr. Zhuanghua Shi

Second Reviewer:

Prof. Dr. Paul Sauseng

External reviewer:

Prof. Dr. Melissa Lê-Hoa Võ

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General Introduction

While concentrating on an ongoing task, such as working on a manuscript in a notebook, our attention can easily be distracted by an irrelevant (visual) pop-out stimulus on the screen (such as an email alert) or a vibrating phone in our pocket (from a pop-up message, see Figure 1B). The underlying mechanisms of how we control our attention and handle distractor interference remain controversial. There has been a long debate about the functional and neural mechanisms underlying attentional capture (for a review, see Luck et al. 2021). It is commonly agreed that both salient stimulus-driven and top-down goal-driven processes compete for attentional control, while context-dependent history effects have been proposed to provide a third pillar of attentional control (Awh, Belopolsky, and Theeuwes 2012). Recently, much of the debate has shifted to the mechanisms underlying distractor inhibition. Top-down theories suggest that target-irrelevant features can be proactively suppressed by a top-down attentional set (Folk, Remington, and Johnston 1992; Leber and Egeth 2006a; Becker, Folk, and Remington 2010) to avoid attentional capture by salient distractors (Gaspelin, Leonard, and Luck 2015). In contrast, bottom-up theories assume that salient distractors always capture attention regardless of the top-down set (Theeuwes 1992; Theeuwes 2010), and distractor suppression comes into play only post capture, by reactive inhibition of and rapid disengagement of attention from the distractor. While the debate between top-down and bottom-up attentional mechanisms remains robust, our primary focus centers on the intricacies of distractor handling, particularly in the framework of proactive versus reactive suppression. Despite their differences, both viewpoints have valuable contributions that we will explore.

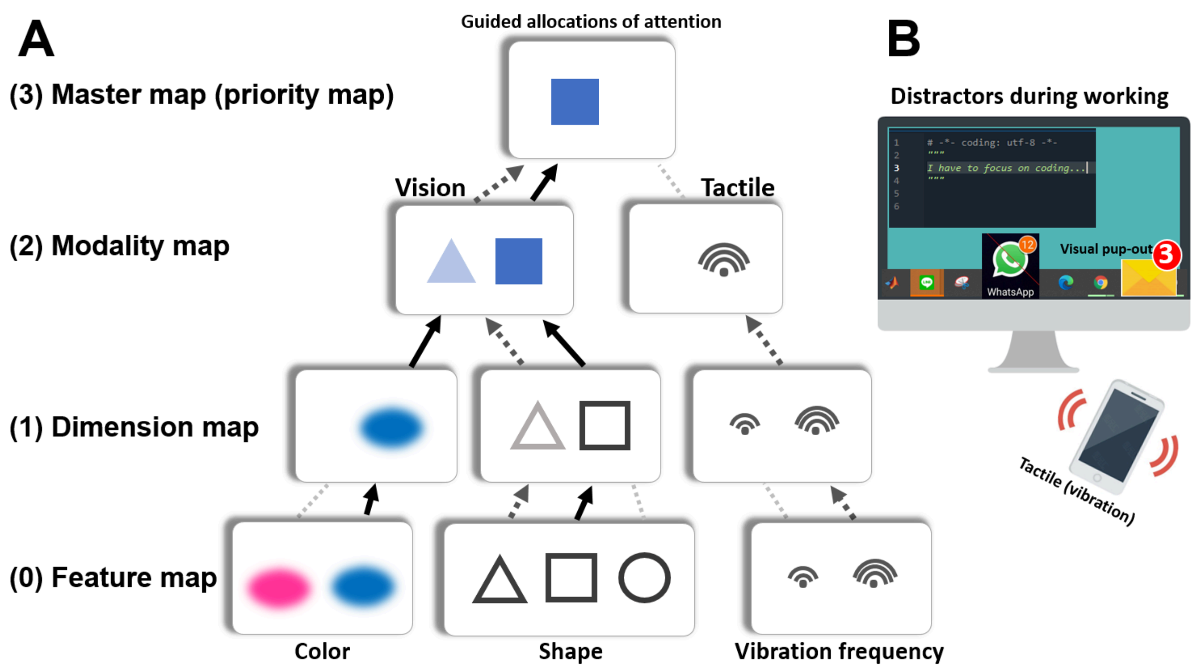

Figure 1. **The hierarchical structure of the Modality-Weighting Account (MWA).** The MWA (Töllner et al. 2009a) suggests that during a visual search task, attention is allocated to different dimensions (e.g., color, shape, frequency) or modalities (e.g., visual, touch) based on their saliency and relevance to the target. The hierarchical structure of the MWA would be as follows: 0. Feature Map: Represents the specific features within each dimension (e.g., blue color, square shape). 1. Dimension Map: Represents the priority of different dimensions within the visual modality (e.g., color and shape). 2. Modality Map: Represents the priority of different modalities (e.g., visual and tactile). 3. Master Map: Computes the weighted sum of dimension-specific and modality-specific saliency signals. For example, if your search target is a blue square. Participants should focus on a blue square target while ignoring a blue triangle (within-dimension distractor), a red circle (cross-dimension distractor), and high-frequency tactile vibrations (cross-modal distractor). According to the dimension-weighting account (DWA, Found & Müller, 1996; Liesefeld & Müller, 2019; Müller et al., 1995, 2003) and MWA, the blue color would be up-weighted, and tactile stimuli would be down-weighted. The MWA's hierarchical structure allows for the efficient allocation of attention to the relevant target (blue square) while minimizing the influence of distractors from other dimensions and modalities.

1.1 Classical Theories of Attentional Control: Stimulus vs. Goal-driven Capture

Strong evidence for stimulus-driven attentional capture comes from the additional singleton paradigm (Theeuwes 1991, 1992). In a typical version of this paradigm, participants are asked to search for a shape singleton (e.g., a diamond among circle non-targets) and respond to the orientation of a bar inside it. Among the non-target items, there may be a color singleton (e.g., a red circle among green circles, with the target diamond also being green). The common finding is that the presence of such an irrelevant yet salient singleton distractor impedes search performance, where the saliency of the distractor relative to the target's is the critical factor for attentional capture (or, theoretically more neutral: interference) to occur (Zehetleitner et al. 2013; Theeuwes 1991, 1992). Bottom-up theories suggest that even though task-irrelevant, a more salient distractor will always capture attention, delaying search for, and responding to, the target item. Note, though, that the saliency of a given distractor may vary as a function of display size – modulating local feature contrast – or, respectively, the featural heterogeneity of the non-target items – generating spurious local feature contrasts (e.g., Liesefeld and Müller 2020). As a result, the same distractor stimulus may not always generate reaction time interference (e.g., Bacon and Egeth 1994; Gaspar and McDonald 2014; Gaspelin, Leonard, and Luck 2015; Wang and Theeuwes 2020).

In contrast to stimulus-driven theories, goal-driven theories propose that it is goal-related features or dimensions, rather than feature saliency as such, that capture attention. For example, Folk et al. (1992) applied a spatial-cueing paradigm (with a spatially non-predictive cue) to illustrate what they refer to as 'contingent attentional capture'. They observed a cue validity effect – that is, slowed RTs when the pre-cue occurred at a non-target vs. the target location, indicative of attentional capture – only when the cue stimulus (e.g., a color cue) was consistent with the target-defining feature (in the example, a color target); a task-irrelevant cue (e.g., an abrupt onset cue followed by a color target), by contrast, failed to elicit a cue validity, or attentional capture, effect. Folk and colleagues (1992) took this to argue that whether or not attentional capture occurs is contingent on the top-down attentional control set adopted by participants (though see Belopolsky et al., 2010, for irrelevant as well as relevant cues capturing attention in a trial-wise, as opposed to a blocked, cueing design). Similar to Folk and colleagues, Bacon and Egeth (1994) proposed that top-down control could override bottom-up attentional capture depending on the search mode participants operate. When observers adopt a 'singleton search' mode (searching for any odd-one-out target among featurally non-targets), a salient distractor can cause substantial interference. In contrast, if they are made to operate in a ‘feature search’ mode (under conditions of feature heterogeneity), interference by salient distractors is greatly reduced. However, it remains controversial whether distractor suppression in feature search mode involves a proactive (Wang et al. 2019; Geng 2014; Huang et al. 2021) or a reactive process (van Moorselaar and Slagter 2019).

1.2 Reconciliation Attempts: The signal suppression hypothesis and rapid disengagement account

Other authors, too, have reported that salient distractors do not always cause interference (e.g., Gaspar and McDonald 2014; Gaspelin, Leonard, and Luck 2015, 2017; Gaspelin and Luck 2018c; Vatterott and Vecera 2012; Won, Kosoyan, and Geng 2019; Wang and Theeuwes 2020). To reconcile the notions of stimulus- and goal-driven attentional capture, Gaspelin and colleagues (2015; 2018c) proposed their ‘signal suppression hypothesis’. Physically salient stimuli possess an intrinsic ‘attend-to-me’ signal to attract attention, electrophysiologically indicated by the N2pc (N2 posterior contralateral, or PCN), a posterior contralateral negativity around 200 ms post stimulus onset; and if this signal is inhibited by processes of cognitive control, a suppression-related P_D (contralateral distractor positivity) component can be observed some 100-400 ms after distractor onset (Hickey, Di Lollo, and McDonald 2009; Sawaki and Luck 2010; Feldmann-Wüstefeld and Vogel 2019). Support for Gaspelin and colleagues’ signal suppression hypothesis comes from reports that a salient distractor elicited a P_D without a preceding N2pc (Gaspar and McDonald 2014; Gaspar et al. 2016; Kerzel and Burra 2020; Gaspelin and Luck 2018a; Sawaki and Luck 2010). For instance, Gaspelin and Luck (2018c, Experiment 2) found a P_D with two distinct peaks, the first phase lasting from approximately 100–175 ms and the second from 175–250 ms. Importantly, the ‘early P_D’ was significantly correlated with behavioral suppression (i.e., reduced identification) of probes presented post search at the distractor location and could be shown, in Experiment 3, not to reflect a Ppc. Gaspelin and Luck (2018c) took the facts (i) that the distractor singletons elicited an early P_D without a subsequent N2pc and (ii) that the P_D correlated with a behavioral index of suppression to “... provide the clearest evidence to date that the P_D reflects suppression of covert attention” (p. 1278).

This notion, of suppression operating prior to any attention shift, is at variance with the ‘bottom-up capture, rapid disengagement’ account (Wang and Theeuwes 2020; Jan Theeuwes 2010). In contrast to the signal suppression hypothesis, the latter account argues that a singleton distractor always captures attention when it is salient enough, and top-down control only plays a role in disengaging attention after it was (mis-)allocated to the distractor. For example, when increasing the set size of the visual search display from four to six and ten, thereby increasing the local feature contrast generated by the singleton distractor, Wang and Theeuwes (2020) found distractor interference (indicative of attentional capture) to be markedly increased and suppression at the singleton distractor location, assessed by means of the post-search probe task (Gaspelin and Luck 2018c; Gaspelin, Leonard, and Luck 2015), to be diminished. Nevertheless, recent work by Zivony and Lamy (2016, 2018) has pointed to a qualitative difference between stimulus- and goal-driven capture: task-irrelevant (color onset) cues only summoned attention (measured by a cue-location effect) but did not 'engage' it (measured in terms of a compatibility effect of the letter at the cued location [in the cue display] with the target letter [in the search display]), while task-relevant (color onset) cues did both capture and engage attention. Of note, though, the capture effect was larger with task-relevant vs. -irrelevant cues.

1.3 Expanding the Scope: Dimension- and Modality-Weighting Accounts

It should be noted that goal-driven attentional control is not limited to target-relevant features; rather, it can also extend to target-relevant dimensions and modalities. The dimension-weighting account (DWA) (e.g., Found and Müller 1996; Müller, Heller, and Ziegler 1995; Liesefeld and Müller 2019; Müller, Reimann, and Krummenacher 2003) and the modality-weighting account (MWA) (Töllner et al. 2009a) posits that the attentional control system dynamically up-weights (i.e., amplify signals in) whole task-relevant dimensions/ modalities (and down-weights task-irrelevant dimensions/ modalities), driven by top-down set as well as inter-trial history. Accordingly, these accounts predict that a salient distractor defined by a different feature within the same dimension or, respectively, the same modality as the target would lead to stronger attentional capture relative to distractors defined in a different dimension, or a different modality – because cross-dimensional and, respectively, cross-modal distractors can be effectively filtered/ suppressed via dimension-/ modality-based attentional weight settings. With regard to dimensions, this has been demonstrated in recent studies of statistical learning of distractor handling (e.g., Goschy et al. 2014; Sauter et al. 2018, 2021; Zhang et al. 2022, 2019; Zehetleitner, Goschy, and Müller 2012; Liesefeld, Liesefeld, and Müller 2019; Won, Kosoyan, and Geng 2019). Following Gaspelin and Luck (2018a, 2018b), Won et al. (2019) have referred to this dimension-based suppression of distractors as 'second-order feature suppression'.

1.4 Rationale of the Studies in this Thesis

As reviewed above, neural mechanisms of (preventing) attentional capture remain elusive as regards the interplay of target- and distractor-related factors. Given this, based on the hierarchical architecture of preattentive priority computation assumed by the DWA and MWA, in the present studies, we systematically manipulated the similarity of the salient distractor to the target-defining feature/ dimension/ modality in additional singleton search task (Study 1, see figure 2A) and target identification tasks (Studies 2 and 3, see figure 2B and 2C), to examine for differential attentional capture effects both behaviorally and electrophysiologically. In particular, we set out to investigate whether down-weighting of the task-irrelevant distractor dimension/ modality involves pro-active suppression or simply lack of attentional engagement, by examining relevant even-related lateralizations (ERL), that is, "difference waveforms" between EEG activity contralateral and ipsilateral to the location of the item of interest. In more detail, the search target was a blue square in Study 1, fixed across the experiments, while the distractor could variably be a blue triangle (different feature), a red circle (different dimension), or a vibro-tactile singleton (different modality). On distractor-present trials, the distractor was presented on the opposite side to the target in target-present conditions, to compete for the lateralized attentional resources. Of note, there was also a target-only condition without any distractor, providing a baseline against which to assess distractor interference effects; and there were target-absent conditions with one distractor (i.e., one of the three types) appearing on any side of the display, to assess the pure potential of a distractor to attract attention (in the absence of competition from the target). Accordingly, given that a target could be either present or absent, the task required participants to discern the presence/absence of a target. Study 2 and Study 3 were similar to Study 1 (see Figure 2B and 2C). We manipulated the targe-distractor similarity. But the target was a blue triangle, and participants should respond to the triangle's orientation (up or down). And the location of the target and distractor were either on the midline or lateral side. Importantly, to control the weighting of dimensions and modalities, we balanced the baseline feature contrasts of all target and distractor items, to equate them in terms of their bottom-up saliency. In addition, we measured attention-related ERLs, in particular: the N2pc (N2-posterior-contralateral), Ppc (Positivity Posterior Contralateral), P_D (Distractor Positivity), CCN/CCP (Central Contralateral Negativity/Positivity), and CDA components.

We provide reasons of selecting these components in the next section.

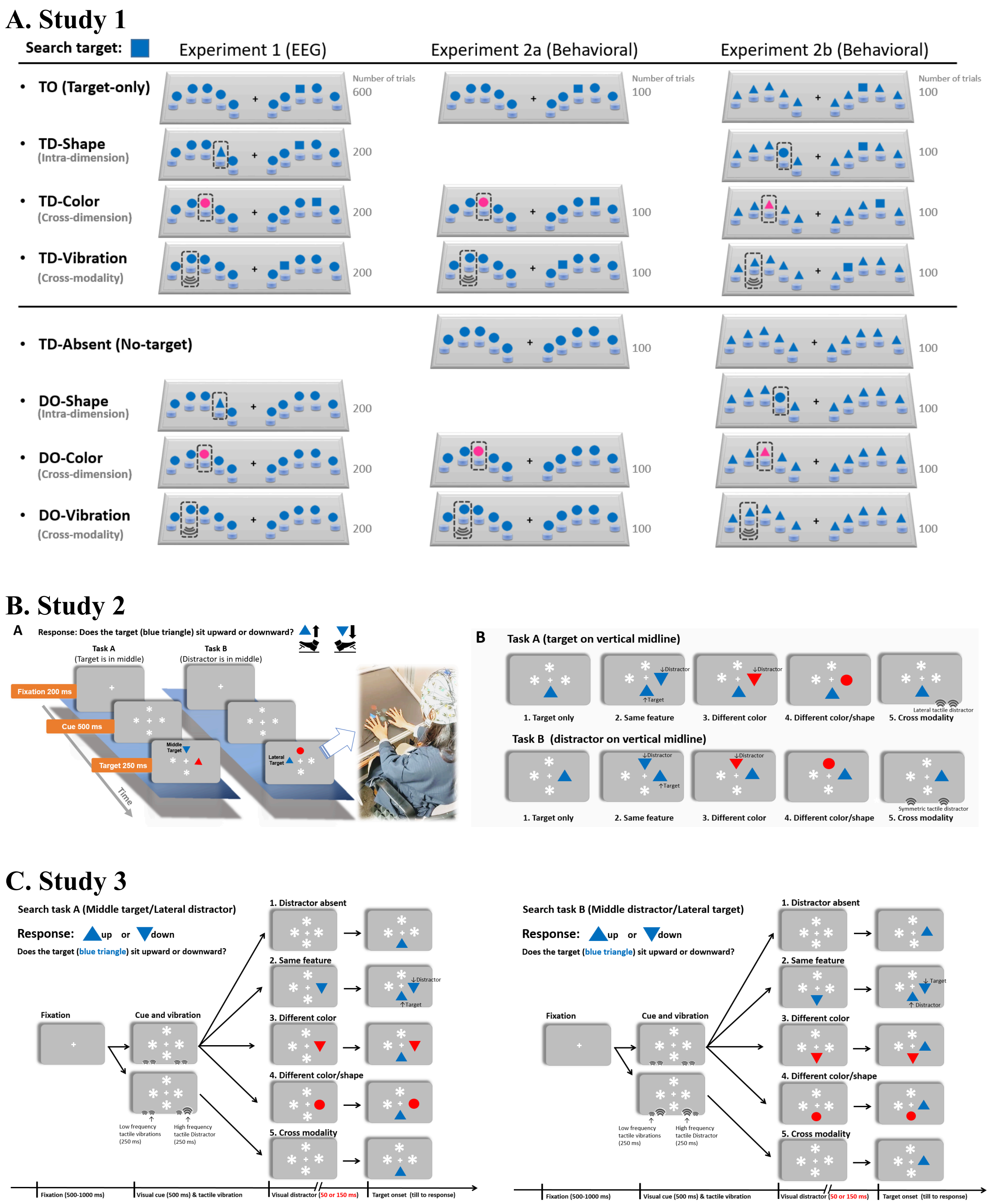

***Figure 2*. Experimental paradigms of the three studies in this thesis. A.** Study 1: All participants placed their fingers on ten tactile vibrators (solenoids) while viewing visual stimuli. Participants responded whether the target, a blue square, appeared or not. Two visual panels represent target-present and target-absent scenarios, respectively. Salient

distractors include shape-defined (blue triangle in Experiment 1, blue circle in Experiment 2b), color-defined (red circle in Experiments 1 and 2a, red triangle in Experiment 2b), and vibro-tactile (distinctive 100-Hz vibration compared to a standard 40-Hz vibration). The location of the target and distractor varied, either on opposing sides or alone. **B.** Study 2: With the same tactile setup as Study 1, participants had to respond to the blue triangle target being up or down by applying foot pedals. Each trial consisted of a 200 ms fixation, 500 ms placeholders, and a 250 ms search display. Different tasks informed participants of target positions either in the middle line (Task A) or laterally (Task B). **C.** Study 3: The tactile and visual setups are similar to those in Study 2. However, the sequence included variable fixation (500-1000 ms), 500 ms placeholders, and the appearance of distractors either preceded the target by 50 ms or 150 ms. Participants identified the orientation of the blue triangle target. The target's location could be middle (Task A) or lateral (Task B). Note: Distractor conditions for Studies 2 and 3 remained consistent across five scenarios: Target-only, Same-feature, Different-color, Different-color and different-shape, and Cross-modality. In Study 3, there's an additional manipulation of the Stimulus Onset Asynchrony (SOA) between the distractor and the target.

1.5 Key Even-Related Potential Components in attentional control

Among the various ERP components, N2pc (also referred to as posterior contralateral negativity, PCN) plays an important role, especially in attentional control. This section will focus heavily on discussing the N2pc. Beyond this key component, we will examine several other important ERP components that collectively give us a broader view of how attentional processes operate. Notably, we'll delve into the CCN (central contralateral negativity), which provides insights into cross-modal attention, and the Ppc (posterior contralateral positivity), giving us a window into early sensory coding. Moreover, the P_D (distractor positivity) component, another pivotal element in our discussion, will help us understand the dynamics of distractor suppression. By examining these components, we hope to build a comprehensive picture of distractor handling, focusing on N2pc and P_D.

The N2pc component – manifesting in activity contralateral to the stimulus of interest (e.g., the target) being more negative than ipsilateral activity around 150–350 ms post display onset – is thought to be a critical neural signature of the lateralized allocation of visuo-spatial attention (e.g., Eimer 1996; Sawaki and Luck 2014; Luck 2011; Luck and Hillyard 1994b; Woodman and Luck 1999; Woodman and Luck 2003). As recently proposed by Zivony et al. (2018), rather than being indicative of visuo-spatial attention shifts as such, the N2pc reflects the attendant engagement of attention at the shift location. To dissociate attentional engagement from shifting, they examined the N2pc in an attentional blink paradigm (with rapid serial visual presentation) with lateralized stimuli. 'Attentional blink' describes the phenomenon that processing (e.g., identification) of a second target (T2) in a serial stream of display frames is impaired when the frame containing T2 follows on the frame containing the first target (T1) within a time window of some 200–500 ms. However, in their adaptation of the attentional blink paradigm, Zivony et al. (2018) still observed that an irrelevant (color) cue presented one frame before the second (color-defined) digit target within the blink window still modulated performance: if T2 appeared at the same (vs. the opposite) location relative to the (color-matching) pre-cue, reaction times (RTs) and accuracy for T2 were improved – indicative of the cue summoning attention even inside (an equally efficiently as outside) the blink period. But despite this attention shift to the location of the cue, participants appeared to have extracted little information from the (digit) item inside the cue – evidenced by the absence of a significant in-/compatibility effect between the cued and the T2 items in the blink window. Zivony et al. reasoned that while attentional shifting is intact within the blink period, attentional engagement is compromised. This behavioral (in-/compatibility) pattern was mirrored in the N2pc elicited by the cue: the N2pc amplitude was markedly reduced (and the N2pc onset somewhat delayed) in response to cues presented inside (vs. outside) the blink period. Zivony et al. (2018) concluded: "Taken together, these results demonstrate that the N2pc does not reflect attentional shifting (which, unlike the N2pc, is unaffected by the blink) but 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).

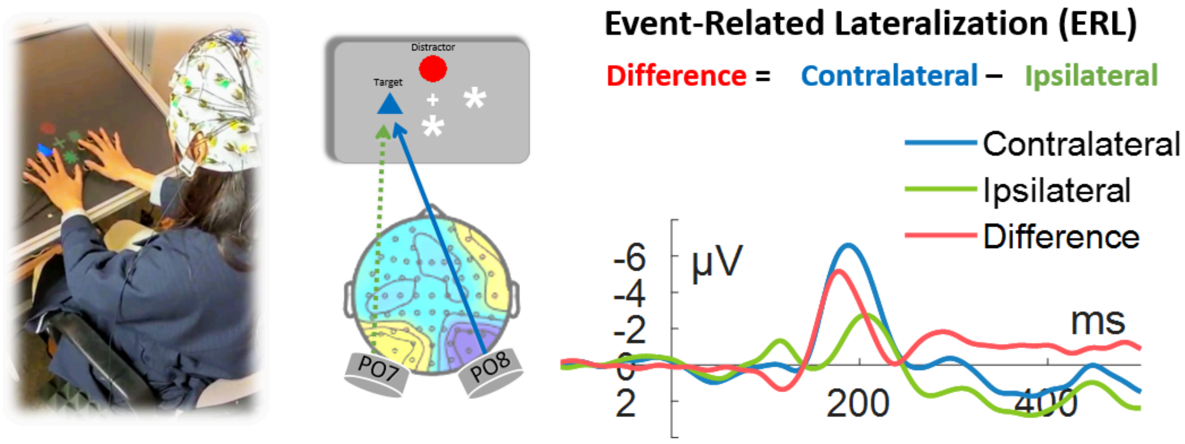

Figure 3. **Event-related lateralization (ERL) demonstrates spatial attention.** ERLs are differential EEG activations between contralateral and ipsilateral sites relative to a target or distractor in a specific location. When a participant is asked to pay attention to a stimulus on one side of their visual field, EEG activity at the contralateral posterior site typically increases, resulting in a difference in waveforms between the contralateral and ipsilateral sites. In this example, the blue triangle on the left side of the visual field is the target. The EEG activity recorded by channel PO8 (blue line) represents contralateral brain activity, as PO8 is contralateral to the target location. Channel PO7 (green line) represents ipsilateral brain activity, as PO7 is ipsilateral to the target location. The red line represents the difference waveform, calculated by subtracting the ipsilateral activity (PO7) from the contralateral activity (PO8) in this case. This difference waveform illustrates the differential attentional processing of the stimulus in the contralateral and ipsilateral hemispheres.

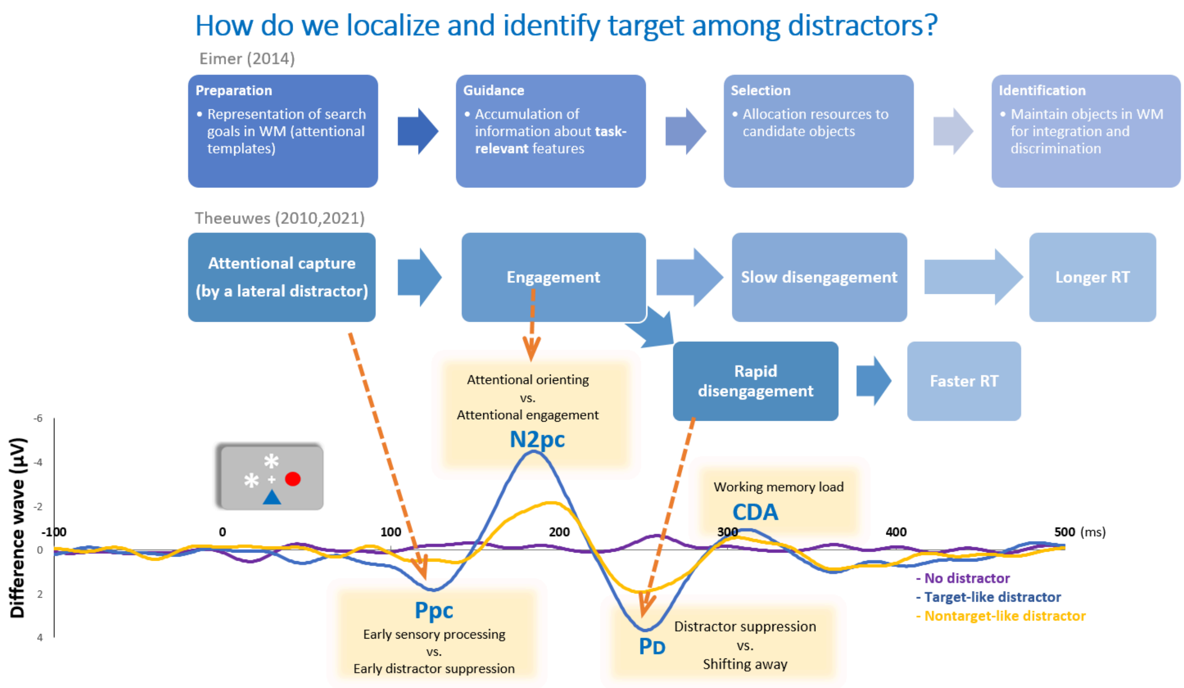

Figure 4. **Attentional processes and the relevant ERL components in visual search.**

According to Eimer (2014), attentional processes in visual search unfold in real-time and can be described by four temporally and functionally dissociable stages of attention: (1) Preparation: the activation of task-relevant representations in working memory and the preparation of attentional control settings. (2) Guidance: the guidance of attention toward task-relevant information. (3) Selection: selecting task-relevant information and suppressing task-irrelevant information. (4) Identification: the identification of the selected target. Theeuwes (2010, 2021) proposed an account of fast disengagement from the distractor, including the following stages: (1) Attentional capture: the involuntary capture of attention by a salient distractor. (2) Engagement: the allocation of attentional resources to the captured distractor. (3) Rapid (vs. slow) disengagement: the disengagement of attention from the previously captured distractor quickly. The speed of disengagement can vary depending on the distractor types. (4) Response: the execution of a motor response to the target stimulus. In our three studies, the goal is to examine and bridge the gap between distinct ERP components and their corresponding attentional processes. The first component, Ppc, might represent early sensory processing or early distractor suppression. This is followed by N2pc, indicative of attentional orienting or engagement. Subsequently, the P_D component emerges, indicates distractor suppression, or shifts away from the distractor. The last component, CDA, is related to working memory load.

Following a similar logic, the three studies in this thesis were designed to examine to what extent distractors defined in either the same feature dimension as the target, or in a different dimension, or in a different modality engage attentional processing resources (where engagement implies that the distractor attracts attention). If a distractor (on one lateral side) engages attention, then, given limited attentional processing resources, fewer resources would be available to process the target (on the other side or midline), giving rise to distractor interference. Besides a behavioral interference effect, this would be evidenced in terms of the N2pc amplitude elicited by the target being reduced on distractor-present vs. distractor absent trials. In contrast, if there is no attentional engagement by the distractor, attentional processing of the target should not be impacted, evidenced by a target-related N2pc amplitude undiminished by the distractor's presence (vs. absence) on the opposite side. The distractor may not engage attention because it is proactively suppressed in the manner envisaged by the signal-suppression hypothesis, that is: upon registration of the presence of the distractor, its location is rapidly (phasically) inhibited, evidenced by a significant distractor-related P_D component on lateral-distractor trials (also for target-absent trials when the lateralized distractor is the only odd-one-out item in the display in Study 1, see Figure 2A) or an enhanced target-related N2pc on target-present trials (with a competing target on the side opposite to the distractor). Alternatively, the DWA and MWA would predict that, at least with cross-dimensional and cross-modal distractors, the whole distractor-defining dimension or, respectively, modality would be tonically down-weighted. That is, odd-one-out signals in the respective dimension or modality, wherever in the display they arise, may be effectively filtered out early on in visual processing, without their presence being registered in the priority computation. Accordingly, there would be no need for a distractor-location-specific suppression process to come into play, and thus no distractor-related P_D would be observed.

A critical and relatively unexplored manipulation in the current study is the use of a cross-modal, tactile distractor in a visual search task, permitting us to investigate attentional capture across modalities. To track tactile (in addition to visual) attentional control, we examined a somatosensory ERL component: the central contralateral negativity (CCN, also referred to as N140cc) – a lateralized negative deflection emerging around 140–340 ms post stimulus over central regions, which is specific to tactile information (Eimer et al. 2004; Forster, Tziraki, and Jones 2016; Eimer and Driver 2000). Previous studies showed the CCN to reflect the allocation of tactile attention (Forster, Tziraki, and Jones 2016; Eimer et al. 2004; Töllner et al. 2009b; Eimer and Driver 2000). In the present study, the lateral vibro-tactile distractors were expected to elicit a significant CCN/CCP. (Of note, the CCP is reversed to the CCN because, in the target-absent condition, the reference is the distractor location.)

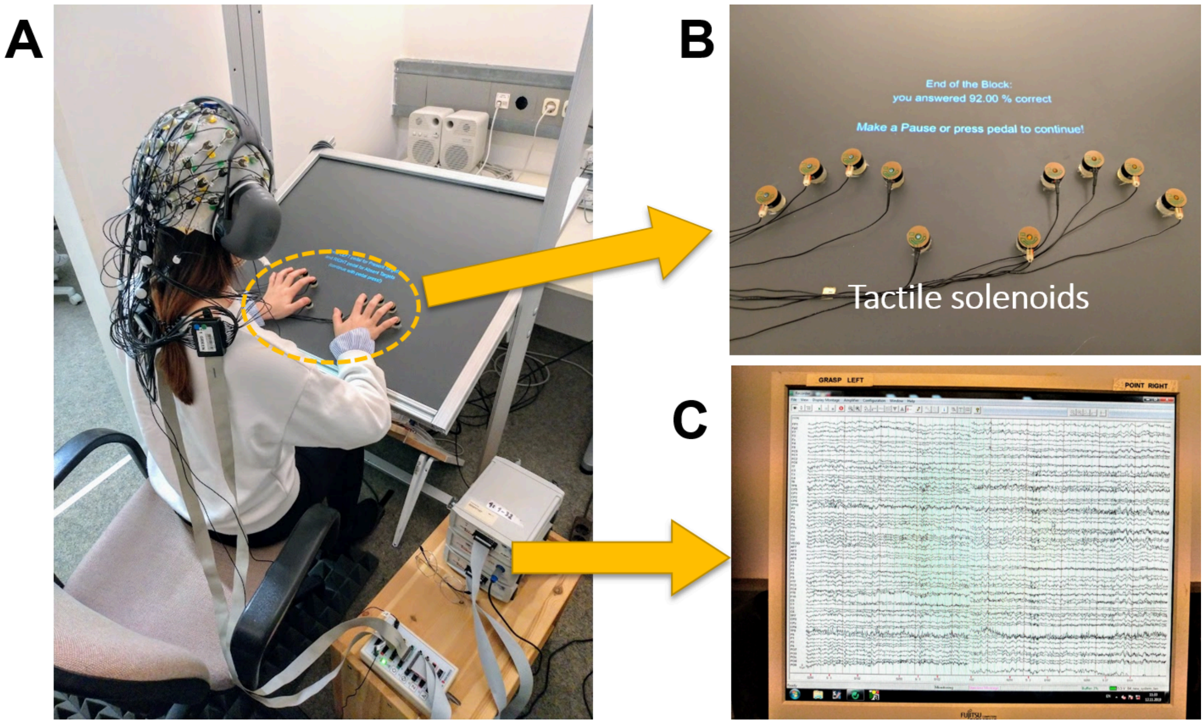

Figure 5. **Schematic illustration of the experimental setup used consistently across all three studies in this thesis.** A: The participant, outfitted with an EEG cap for real-time brainwave recording, is shown comfortably seated on a chair. Their fingers are gently placed on tactile solenoid vibrators, poised to sense the vibrations generated during the experiment. In front of the participant is an inclined screen, where the visual search array is displayed via a rear projector. The screen is positioned at a viewing distance of approximately 55 cm from the central fixation marker, with visual stimuli presented near the tips of the participant's fingers. Participants make responds using foot pedals. This setup allows for an engaging multisensory experiment, incorporating simultaneous visual and tactile stimuli. B: A magnified view of the tactile solenoid vibrators. Each solenoid, with a diameter of 1.8 cm, is situated directly beneath the visual items on the screen, transmitting corresponding tactile stimuli to the fingers. C: An instantaneous depiction of the EEG data being recorded during the attention task.

One early, positive component emerging around 100 ms post stimulus onset and thus preceding attentional allocation is the so-called positivity posterior contralateral (Ppc), which *may* be elicited by a salient (lateral) visual target or distractor. The Ppc is thought to reflect sensory coding processes in early visual cortex (Störmer, McDonald, and Hillyard 2009; Woldorff et al. 1997; Itthipuripat et al. 2014; Luck and Hillyard 1994a). In particular, the Ppc reflects perceptual enhancement of the search display item upon 'contingent' capture of attention by a pre-cue possessing a task-relevant feature (Livingstone et al. 2017), and the component's attentional gain correlates with improved target detection (G. R. Mangun and Hillyard 1990, 1991).

In addition, we measured the contralateral delay activity (CDA) component. The CDA, which usually emerges some 200 ms after stimulus onset, is thought to reflect the processing of attentionally selected stimuli in visual working memory (Chen et al. 2022; Mazza et al. 2007; Vogel and Machizawa 2004; Woodman and Vogel 2008; Töllner et al. 2013). Accordingly, the CDA could be taken to index the efficiency of focal-attentional processing. In the target-only condition, the target – being the only salient display item – would invariably be selected into vWM and fully engage the available resources at this focal-attentional processing stage – manifesting in a significant target-elicited CDA. However, in the presence of an interfering distractor, the target may be selected into vWM along with the distractor (consistent with, e.g., Bundesen's (1990) 'theory of visual attention' or Wolfe's (2003) 'car-wash' metaphor of post-selective processing); or, alternatively, only the target is selected on some trials and only the distractor on others (whichever item wins the competition for selection). This would effectively force a sharing of the post-selective processing resources, either on the same trial or statistically across trials – leading to a diminished CDA.

1.6 The Aims of This Thesis

The overall goal of this thesis is to unravel the complex mechanics of how our attentional system interacts with a stimuli-rich environment where distractors abound in various forms, varying in their features, dimensions, and modalities. It's part of a theoretical framework that aims to understand the neural correlates of attentional control and distractor suppression by analyzing EEG indexes like the N2pc and P_D. The focus is to comprehend how attention is modulated across different hierarchical levels of attention, namely, feature, dimension, and modality.

Core Questions:

1. Hierarchical Structure of Attention: At the heart of this thesis lies the question of how attention is systematically guided or distracted at various hierarchical levels. How do intra-dimensional distractors influence attention compared to cross-dimensional and cross-modal distractors? This question seeks to elucidate the dynamics of attentional control in a complicated environment, focusing on distractor-target relationships within the same and different attentional hierarchies.
2. Neural Mechanisms of Attentional Control: Following the first question, we explore the neural underpinnings of these attentional dynamics. How do distractors modulate neural markers such as the N2pc, Ppc and P_D components?
3. Distractor Suppression Strategies: Going further, this research seeks to understand the proactive and reactive suppression strategies employed in dealing with different types of distractors. Does the brain have a different approach to dealing with distractors of varying dimensions and modalities?

By systematically manipulating the relation of the distractor to the target (intra-dimension, cross-dimension, cross-modal definition of the distractor), we examined for potentially diminishing distractor inference across the hierarchical levels feature, dimension, and modality weighting, both behaviorally and in terms of ERP signatures (in particular, the N2pc and P_D components). According to the notion of dimension-based distractor handling (Liesefeld and Müller 2019) – and, by extension, that of modality-based distractor handling –, we expected (1) the intra-dimension distractor (i.e., a distractor defined within the same dimension as the target) to draw attentional resources most prominently, since dimension-based down-weighting would be a non-optimal strategy to perform the task: down-weighting of any feature-contrast signals in the distractor-defining dimension would reduce not only the deployment of processing resources to the distractor (beneficial effect), but also the processing of the target (harmful effect). Hence, in this condition, attention may be distributed equally to the target and distractor, leading to a reduced target-elicited N2pc. In contrast, (2) cross-dimensional distractors (i.e., distractors defined in a different visual dimension to the target) and, respectively, cross-modal distractors (i.e., distractors defined in a different modality to the target) can be relatively effectively down-weighted without impacting target processing. That is, cross-dimension or cross-modal distractors can be effectively filtered out, so that the target could more or less fully engage attention – leaving the target-elicited N2pc relatively unaffected in the presence of such a distractor. In contrast, if the distractor dimension or modality cannot be effectively down-weighted, a cross-dimensional or, respectively, cross-modal distractor would engage attention and fewer resources would be allocated to the target – manifesting in a reduced target-elicited N2pc. (3) The cross-modal, vibro-tactile distractor would be expected to elicit a CCN. If the target-elicited N2pc remains unaffected by the presence of such a distractor, one would infer that the cross-modal distractor captures attention without further engagement.

The three studies in this thesis will provide a better understanding of how distractions are handled. The process of distractor suppression is unclear, as some studies suggest proactive suppression, while others suggest reactive suppression. Based on the experimental design, participants might apply different suppression strategies. In Studies 1 and 2, we expect that down-weighting (based on DWA/MWA) would work well to handle the distractor in a proactive suppression manner. In Study 3, proactive suppression may fail to avoid attentional capture by the distractors. Therefore, participants still need to apply reactive suppression to disengage from the distractor and reorient to the target. Therefore, we would expect to see a significant P_D component following the N2pc component. It shows the lateral distractor would capture participants' attention, and the distractor-elicited N2pc component indicated attentional engagement with the distractor. Afterward, they need to disengage from the distractor, so the P_D component can represent disengagement. However, the precise meaning of P_D is very controversial. We will discuss this in the last chapter, the general discussion.

Cumulative Thesis Note

This thesis is built upon three separate studies detailed in the subsequent chapters:

Chapter 2 (Study 1): This chapter embodies a study that has been peer-reviewed and published in *Psychophysiology* in 2023.

Chapter 3 (Study 2) and Chapter 4 (Study 3): These chapters present manuscripts in the pipeline for submission to peer-reviewed academic journals.

Each study is an essential component of this thesis, contributing to the cumulative knowledge and insights presented. To maintain transparency and adhere to academic norms, a "Declaration of Author Contributions" has been included in the final part of this thesis. That section delineates the specific contributions of each author involved, aiming to prevent any future disputes over authorship.

Chapter 2: Little Engagement of Attention by Salient Distractors Defined in a Different Dimension or Modality to the Visual Search Target

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

Shao-Yang Tsai, Jan Nasemann, Nan Qiu, Thomas Töllner, Hermann J. Müller, & Zhuanghua Shi

Ludwig-Maximilians-Universität München, 80802 München, Germany

Author Note

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

2.1 Introduction

While engaged in a task, such as writing a manuscript, it's 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 Steven J. 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 is 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- (Folk, Remington, and Johnston 1992; Leber and Egeth 2006a; Becker, Folk, and Remington 2010), or dimension-based (Müller, Heller, and Ziegler 1995; Liesefeld, Liesefeld, and Müller 2019; Liesefeld and Müller 2020) stimulus set, preventing (or, at least, minimizing) attentional capture by salient distractors in the first instance (Gaspelin, Leonard, and Luck 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.

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, Leonard, and Luck 2015, 2017; Gaspelin and Luck 2018c; Vatterott and Vecera 2012), if the prevalence of distractors is high (e.g., Geyer, Müller, and Krummenacher 2008; Müller et al. 2009; Won, Kosoyan, and Geng 2019), or if the distractor occurs at a predictable display location (e.g., Allenmark et al. 2019; Goschy et al. 2014; Sauter et al. 2018; Zhang et al. 2019; Wang and Theeuwes 2018; Won, Kosoyan, and Geng 2019; Ferrante et al. 2018) – 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 and Müller 1996; Müller, Reimann, and 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., J. Krummenacher, Müller, and Heller 2001; Joseph Krummenacher, Müller, and Heller 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]

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; Sauter et al. 2018, 2021; Zhang et al. 2022, 2019; Zehetleitner, Goschy, and Müller 2012; Liesefeld, Liesefeld, and Müller 2019; Won, Kosoyan, and Geng 2019). We attributed the interference reduction by cross-dimensional distractors to the operation of 'dimension-based' suppression[2]. Following Gaspelin and Luck (2018a, [b] 2018), 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'.

[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 et al. (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.

[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'.

An extension of the DWA is the 'modality-weighting account' (MWA) proposed by (Töllner et al. 2009a) (2009a) 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 or 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 color distractor in Experiment 3 would not elicit a P_D because there is little need for suppression to select the more salient color target. And, to explain the reduced P_D elicited by the same (red) color-defined distractor in Experiment 2 vs. 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

[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).

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 and Müller 2021, Appendix 4). In fact, to account for dimension-based inter-trial effects, Müller and colleagues (Krummenacher, Müller, and Heller 2002; Krummenacher, Müller, and Heller 2001; e.g., Found and Müller 1996; Müller, Reimann, and 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 & 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

[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, Liesefeld, and Müller 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.

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.

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.

Stimulus and task design

The basic set-up of *collocated* visual and tactile stimuli is illustrated in Figure 1. Of note, this set-up was adopted from Töllner et al. (2009a), 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 set-up (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 1).

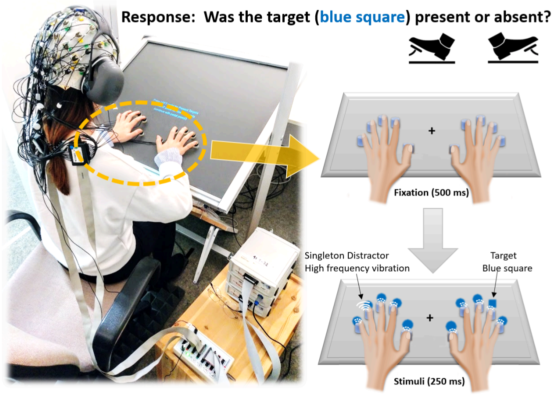

Figure 1 Schematic illustration of the experimental setup. Participants sat on a chair, with their fingers placed on tactile (solenoid) vibrators, watching the visual search array that consists of 10 items projected near the tips of their fingers and sensing the solenoid-generated vibrations below their 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.

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 set-up 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, Di Lollo, and McDonald 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 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.

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; Sawaki and Luck 2014; Luck 2011; Luck and Hillyard 1994b; Woodman and Luck 1999; Woodman and Luck 2003; Sawaki and Luck 2010): 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] 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

[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.

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 set-up, 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 (Forster, Tziraki, and Jones 2016; Martin Eimer et al. 2004; M. Eimer and Driver 2000; Töllner et al. 2009a). 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 (Leblanc, Prime, and Jolicoeur 2008; e.g., Jannati, Gaspar, and McDonald 2013), have also been observed in visual search studies. As the Ppc can be elicited by both target and nontarget singletons, it has been taken to indicate an early, low-level sensory asymmetry (Luck and Hillyard 1994b) or, respectively, an ‘attend-to-me’ signal (e.g., Jannati, Gaspar, and McDonald 2013; McDonald et al. 2023; Sawaki and Luck 2010; Stilwell, Egeth, and Gaspelin 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 and Luck 2010; Stilwell, Egeth, and Gaspelin 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, Uengoer, and Schubö 2015; Feldmann-Wüstefeld and Schubö 2013; Hilimire and Corballis 2014; Gaspar and McDonald 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., M. Eimer 1996; Sawaki and Luck 2014; Steven J. Luck 2011; Luck and Hillyard 1994b; G. F. Woodman and Luck 1999; Geoffrey F. Woodman and Luck 2003; Sawaki and Luck 2010; Jannati, Gaspar, and McDonald 2013; McDonald et al. 2023) – 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; Vogel and Machizawa 2004; Geoffrey F. Woodman and Vogel 2008; Töllner et al. 2013). 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 and 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’.

2.2 Experiment 1

2.2.1 Method

2.2.1.1 Participants

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 (Nasemann et al. 2023; Chen et al. 2022) 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.

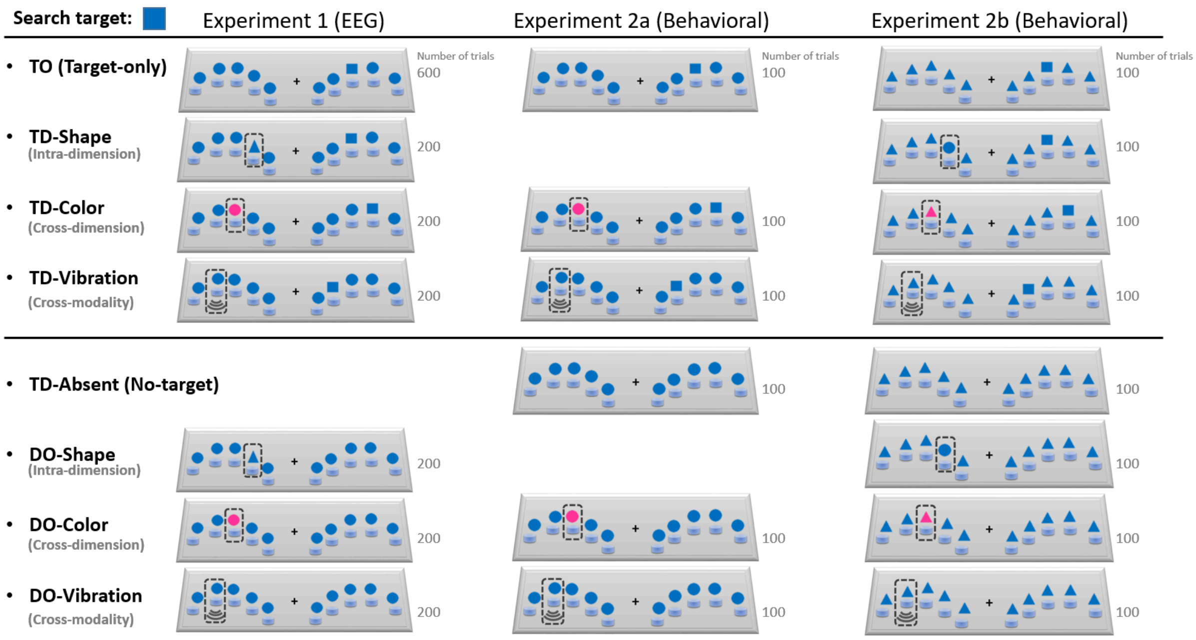

Figure 2 Types of search arrays used in Experiments 1 and 2. The target was a blue square across all experiments. The search arrays are grouped according to the response category: the upper panel were the target-present displays, and the lower panel the target-absent displays. There were three types 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.

2.2.1.2 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, Brainard, and Pelli 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° towards 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/m²), and tactile amplitudes were aligned (40 Hz or 100 Hz). The basic features (color, shape, luminance, and vibration intensity were selected based on a series of pilot experiments (see Appendix 1), 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.

2.2.1.3 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 nother 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 trials). The conditions were intermixed and randomized within a block. To

[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.

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 2-b), 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.

2.2.1.4 EEG recording and preprocessing

EEG data was 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 and 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 and Sejnowski 1995; Lee, Girolami, and Sejnowski 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%).

2.2.1.5 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 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 below 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, Rangelov, and Müller 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 one the default simple t-test with a Cauchy prior ($0, r = 1/\sqrt{2}$) from JASP (Wagenmakers et al. 2017).

2.2.2 Results

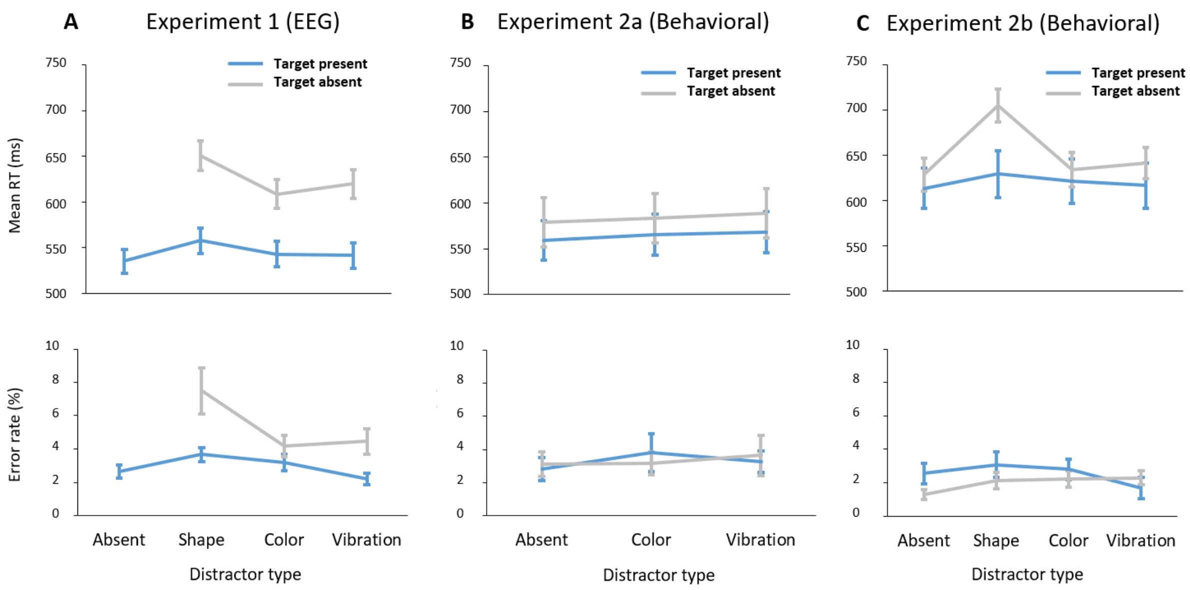

Figure 3 Mean RT (upper panel) and error rate (lower panel) as a function of the distractor type, separately for target-present (blue) and target-absent (gray) trials, separated for individual experiments. Error bars represent one standard error of the mean.

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}
Experiment 1					
Target	1, 20	154.34	< 0.001*	0.885	> 100
Distractor type	2, 40	70.64	< 0.001*	0.779	> 100
Target × Distractor type	2, 40	12.23	< 0.001*	0.379	> 100
Experiment 2a					
Target	1, 17	7.50	0.014*	0.306	2.701
Distractor type	2, 34	13.03	< 0.001*	0.434	63.520
Target × Distractor type	2, 34	0.21	0.805	0.013	0.513
Experiment 2b					
Target	1, 17	13.89	0.002*	0.450	> 100
Distractor type	2, 34	92.60	< 0.001*	0.845	> 100
Target × Distractor type	2, 34	64.32	< 0.001*	0.791	> 100

Error rate	*df*	*F*	*p*	η_p^2	BF_{incl}
Experiment 1					
Target	1, 20	18.12	< 0.001*	0.475	> 100
Distractor type	2, 40	8.45	< 0.001*	0.297	88.337
Target × Distractor type	2, 40	4.23	< 0.001*	0.174	16.08
Experiment 2a					
Target	1, 17	<0.01	0.982	<0.001	0.214
Distractor type	2, 34	0.406	0.670	0.023	0.122
Target × Distractor type	2, 34	0.513	0.603	0.029	0.032
Experiment 2b					
Target	1, 17	1.21	0.286	0.067	0.562
Distractor type	2, 34	1.84	0.152	0.098	0.372
Target × Distractor type	2, 34	2.93	0.042*	0.147	0.798

2.2.2.1 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 Target (Target (present, absent) × Distractor-Type (Shape, Color, Vibration) ANOVAs 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 target-absent vs.

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 towards 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 vs. 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 vs. Color (28 ms, $p < .001$), Shape vs. Vibration (15 ms; $p < .001$), Color vs. 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 2 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 (Joseph Krummenacher, Müller, and Heller 2002; Müller, Heller, and

Ziegler 1995; e.g., Chun and Wolfe 1996), 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 an analysis of the singleton-only RTs as a function of the eccentricity of the target (see Appendix 3): 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 A3). 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.

2.2.2.2 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 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.

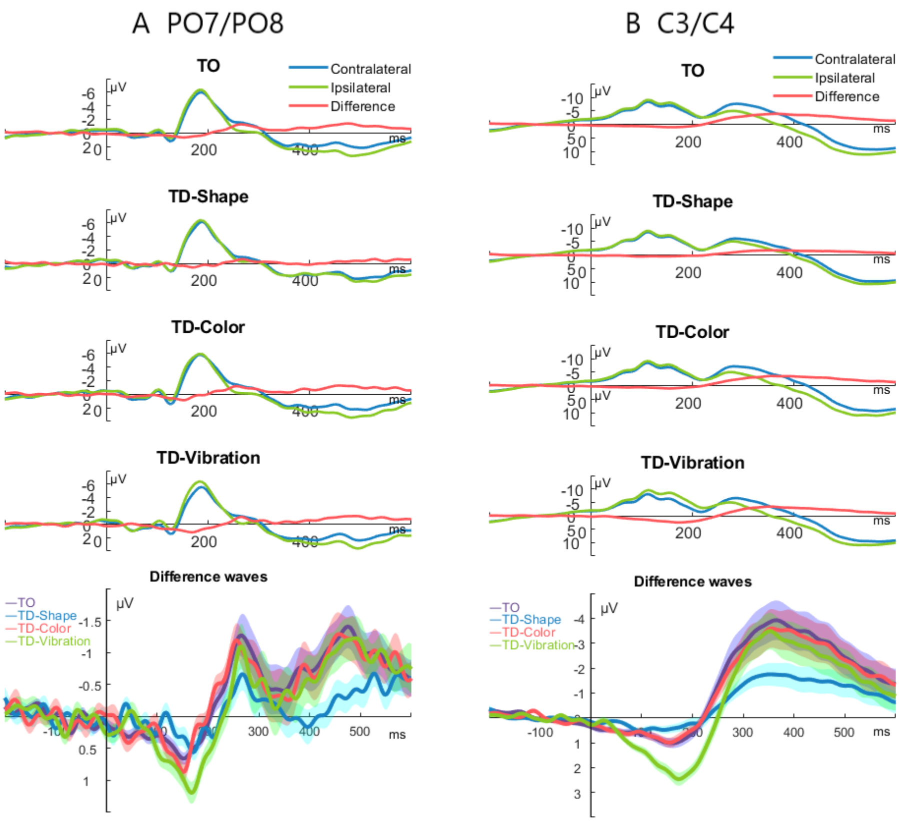

Figure 4 ERPs elicited contra- and ipsilateral to the target location for the four types of target-present trials (factor: Distractor Type) from electrodes PO7/PO8 (A) and, respectively, C3/C4 (B). Difference waves indicate contralateral minus ipsilateral waves, referenced to the target location/side (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.

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)
Target-present (Four levels: TO, TD-Shape, TD-Color, and TD-Vibration)							***Mean (SD)***			
N2pc (PO7/PO8)	200 – 300 ms	3, 60	5.992	0.001**	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	< 0.001***	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	< 0.001***	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	< 0.001***	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	0.002**	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	< 0.001***	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	0.859	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	0.094	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	< 0.001***	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	0.001**	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).

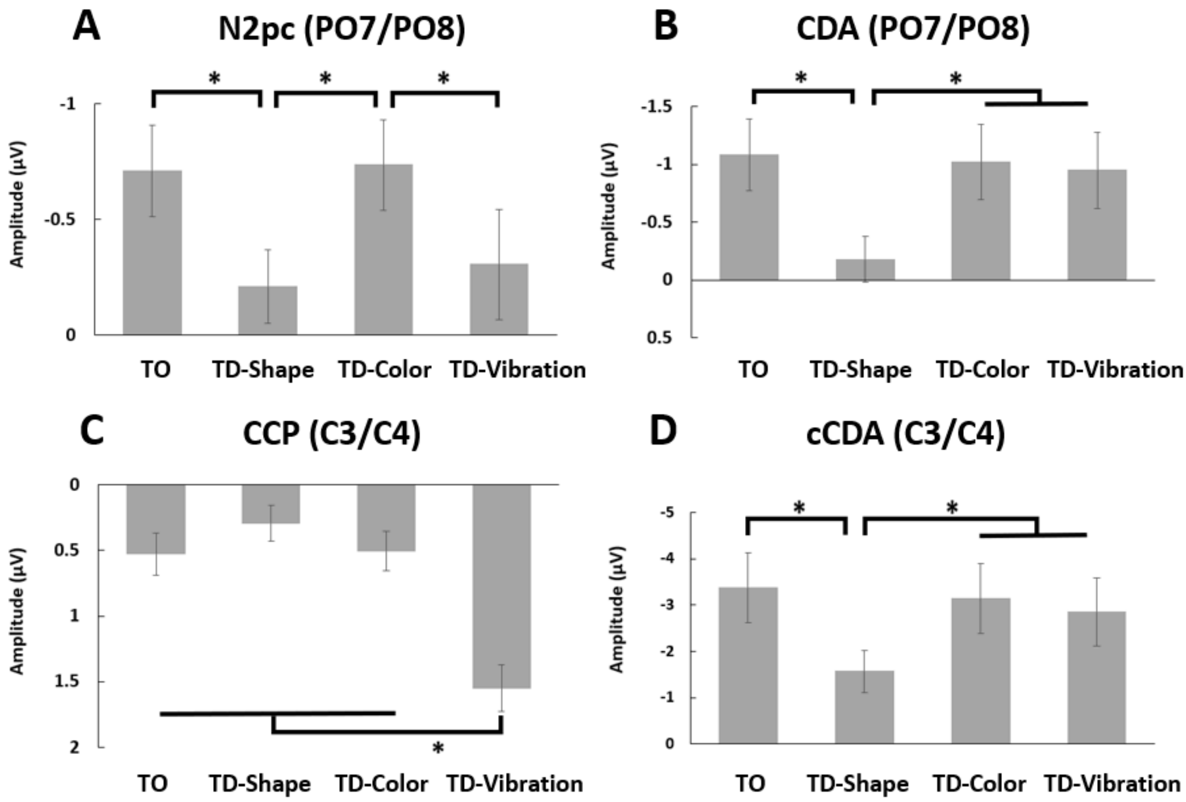

Figure 5 Amplitudes of the ERL components from PO7/PO8 and, respectively, C3/C4 on target-present trials, separately for the four distractor conditions. (A) N2pc amplitude within the 200–300 ms time window. (B) CDA amplitude in the 400–500 ms window. (C) CCP amplitude within the 50–250 ms time window.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

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 (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 of the (*peak*) amplitude of the N2pc in the TD-Vibration vs. 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 of 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 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 < 0.001), 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

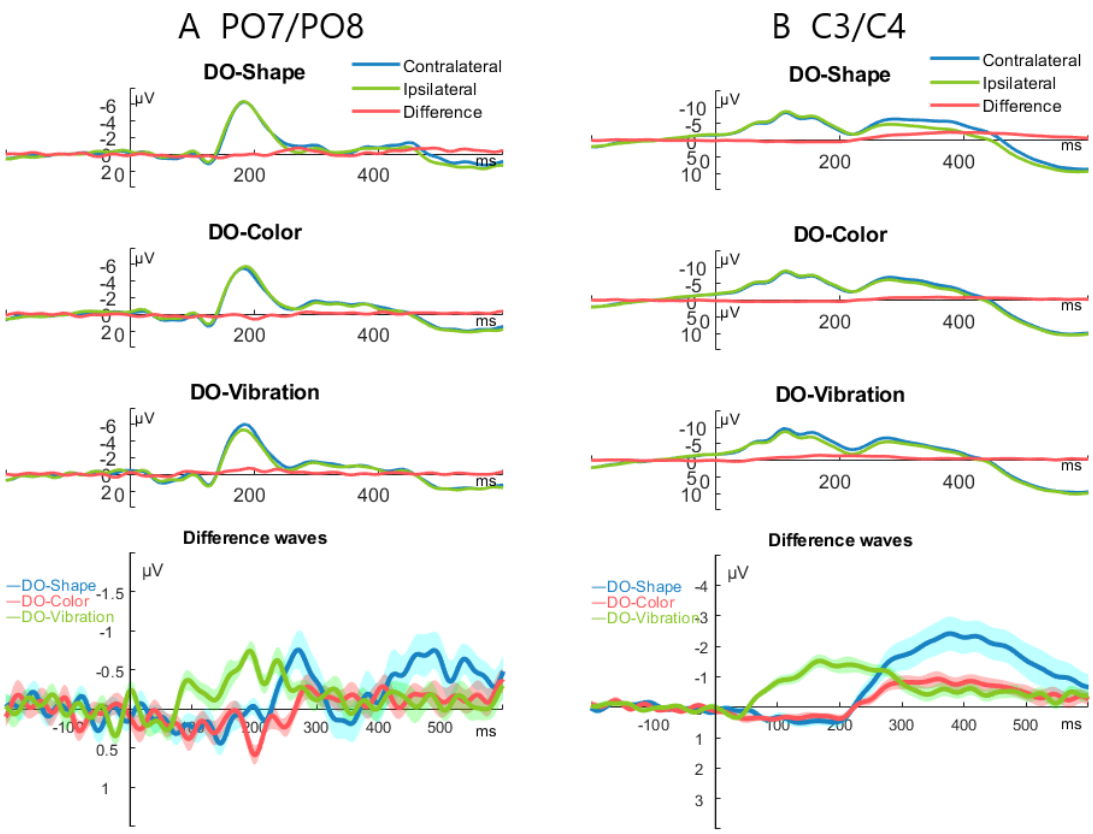

Figure 6 ERPs elicited contralateral and ipsilateral to the distractor location for the three types of target-absent trials (factor: Distractor Type) from electrodes PO7/PO8 (a) and, respectively, C3/C4 (b). Difference waves indicate contralateral minus ipsilateral waves, referenced to the distractor 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.

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 distrator-referenced ERL components: the N2pc, Ppc, late P_D, CDA, cCDA, and CCN.

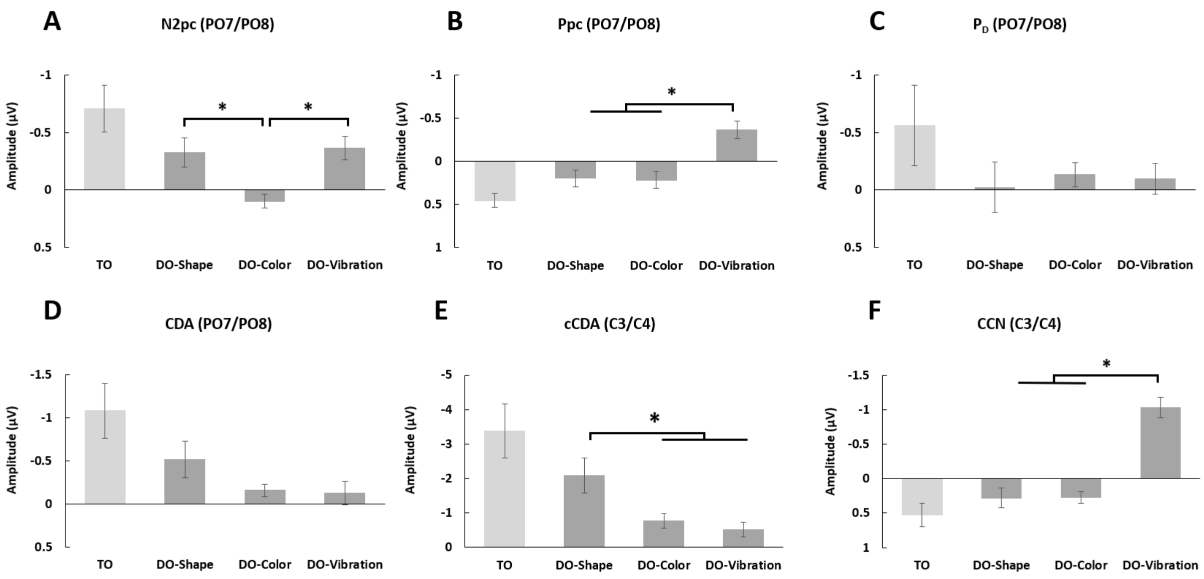

Figure 7 Amplitudes of the ERL components from PO7/PO8 and C3/C4 on target-absent trials, separately for the three distractor conditions; for reference and comparison, the ERLs are also depicted for the target-only (TO, light gray) condition, in which displays likewise contained only one singleton item, 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 $p < .05$.

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 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 and 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) vs. the other DO conditions (ps < .007). Note, though, that all CDA and cCDA amplitudes were significantly negative (except that of the CDA in the DO-Vibration condition), but the amplitudes were significantly smaller even in the DO-Shape vs. 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 (*p*s > .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 (seeFigure 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 at the expense of the 'enhancement' for the target signal, a process known as 'normalization' (Reynolds and Heeger 2009; Louie, Khaw, and Glimcher 2013). 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- vs. slow-RTs trials, which would be expressed in an N2pc amplitude difference. However, as can be seen from Figure 6, 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 > 0.210). 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 M. M. Müller et al. 2003).

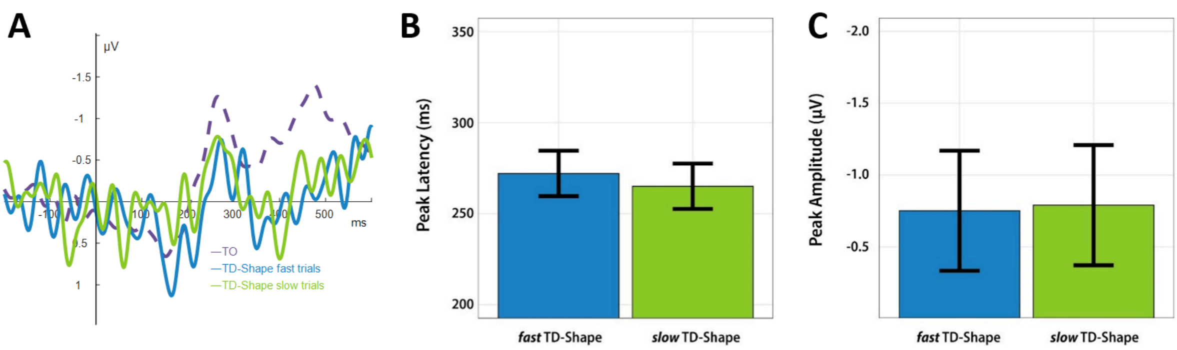

Figure 8 (A) Contralateral minus ipsilateral difference waves, referenced to the target-side, for the fastest-RT trials (blue) vs. the slowest-RT trials (green), with the target-only (TO) baseline (dashed) for comparison. (B) Mean N2pc (peak) latencies and (C) N2pc (peak) amplitudes for the three conditions;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

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

2.3 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 and Egeth 1994; Liesefeld et al. 2019; Theeuwes, Bogaerts, and van Moorselaar 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.

2.3.1 Method

2.3.1.1 Participants

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

2.3.1.2 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 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 nontarget and target shapes relative to Experiment 1).

2.3.1.3 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 nontarget 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.

2.3.2 Results

Figure 3B and 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 (*p*s > .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 vs. absent, exhibiting the typical Target effect. Further, RTs were somewhat slowed (12 ms, $p < .01$) by the presence vs. 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 (*p*s > .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 3) 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 A3). 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 vs. 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.

2.3.3 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

[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, Hanks, and Geng 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?

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 (Müller, Heller, and Ziegler 1995; Found and Müller 1996; Liesefeld and Müller 2019), 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 (2006b, [a] 2006), 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, Goschy, and Müller 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.

2.4 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 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, Gaspar, and McDonald 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 and Müller 1996; Liesefeld and Müller 2019; Müller, Heller, and Ziegler 1995; Töllner et al. 2009a). 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.

2.4.1 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 (Duncan and Humphreys 1992; Folk, Remington, and Johnston 1992; Wolfe and Horowitz 2004; Bacon and Egeth 1994) to top-down bias search towards 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 and Müller 1996; Liesefeld and 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,

[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 and 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 and Müller 1996).

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 and Müller 2019; Zhang et al. 2019; Müller, Heller, and Ziegler 1995) – a pattern confirmed 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 4). Together with the analysis of the timing and amplitude of the N2pc on fast- vs. slow-RT trials (see section 2.2.2 above), 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 re-actively 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; Töllner, Mink, and Müller 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 N2pc's 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.

2.4.2 Cross-modal distractor handling

The modality-weighting account (MWA, Töllner et al. 2009a) 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).

2.4.3 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 2021, 2010). 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; Theeuwes 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 and Egeth 1994; Chang and Egeth 2019; Gaspelin, Leonard, and

Luck 2015; Gaspelin and 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 towards 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 and Egeth 1994; Chang and Egeth 2019; Gaspelin, Leonard, and Luck 2015; Gaspelin and 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 and 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

[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 Steven J. Luck et al. 2021) and not compatible with the original rapid-disengagement account.

present study, which may have forced participants to adopt a parallel, rather than a serial, attention-allocation strategy (Martin Eimer and Grubert 2014). 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 and Luck 2018a; Gaspelin, Leonard, and Luck 2015; Gaspelin and Luck 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 vibro-tactile 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, Xu, and Lleras 2019; Grüner, Goller, and Ansorge 2021; Wolfe and Horowitz 2004, 2017; Xu, Lleras, and Buetti 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

[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).

P_D is strictly necessary for successful *pro-active* distractor handling.

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 for *target*-dimension weighting in the absence of a stimulus, see (operating even in the absence of, i.e., 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 and Luck 2018c; Steven J. Luck et al. 2021), and sometimes processes that do not involve a P_D (e.g., Gaspar and McDonald 2014; van Moorselaar and 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.

2.4.4 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.

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2.6 Appendices

Appendix 1. Pilot studies

In there pilot experiments prior to testing (shared with Nasemann et al., 2023), we attempted to ensure that the odd-one-out salient target (blue square) and distractor (blue triangle, magenta circle, 100 Hz tactile vibration) stimuli were of comparable physical feature contrast or bottom-up saliency. In more detail, following Zehetleitner et al. (2013), the pilot study used the detection task, requiring an odd-one-out signal present vs. absent decision, to match the saliency of the target and distractor feature-contrasts among the non-target items (blue circle, 40 Hz vibration) in our crossmodal search display, by comparing error rates (ERs) and RTs. In a first pilot experiment (N = 8), the blue square target (among blue circles) and the 100 Hz tactile frequency target (among 40 Hz non-targets) turned out most similar (ERs: 6% vs. 9%, $p = .057$; RTs: 570 ms and 567 ms, $p = .93$) [in comparison to 5 other tactile target/non-target frequency pairings]. In the second pilot experiment (N = 10), we compared five (circle) colors from the red-to-blue spectrum and the 100-40 Hz tactile frequency pairing, where the blue square (RGB: [0 0 255]; 10%, 547 ms) turned out comparable to a magenta (circle) color (RGB: [101 0 135], 6%, 567 ms) and the 100-40 Hz tactile frequency pairing (10%, 618 ms) (ERs, $p > .054$, RTs, $p > .102$). A third pilot experiment (N = 19) compared the blue square against a blue triangle (with the triangle size aligned to cover a similar area as the square), which yielded near-equal performance (blue square: 2%, 563 ms; blue triangle: 3%, 560 ms). This way, we could be reasonably confident that the odd-one-out target and distractor stimuli used in the main experiment were similarly competitive for attentional selection.

Appendix 2. Learning of distractor suppression

We further examined how the ability to handle distraction changes with experience (i.e., over the course of the experiment) with the different types of distractor. Figure A1 presents the RT interference (the difference between the respective distractor-present conditions vs. the target-only condition) as a function of the experimental block number. On target-absent trials (with only a distractor in the display), the intra-dimension Shape distractor induced the largest interference, with interference staying high over time-on-task; in contrast, Color and Vibration distractors appeared to produce some interference early on, which diminished over time-on-task. On target-present trials, the interference from the Shape distractor remained higher compared to the Color and Vibration distractors, with the latter two producing minimal interference. We estimated these trends using linear regression for individual participants in each condition. In the target-absent conditions, mean slopes (and associated standard errors) were 0.48 (±0.83), –1.26 (±0.91), and –1.91 (±1.07) ms/block with the Shape, Color, and Vibration distractors, respectively; this compares with –0.78 (± 0.28), –0.04 (±0.35), and –0.09 (±0.32) ms/block in the corresponding target-present conditions. A repeated-measures ANOVA of the slopes, with the factors Target and Distractor Type, revealed the interaction to be significant, $F(2, 40) = 9.68$, $p < .001$, $BF = 2.7$ (both main effects were non-significant: Target, $F(1, 20) = 0.45$, $p = .51$, $BF = 0.36$; and Distractor Type: $F(2, 40) = 2.63$, $p = .08$, $BF = 0.17$). The interaction reflects the opposite trends in the target-present vs. -absent conditions. Thus, there is 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 also Zhang et al. 2019, for participants requiring experience with color distractors to "discover" the optimal, dimension-based suppression strategy).

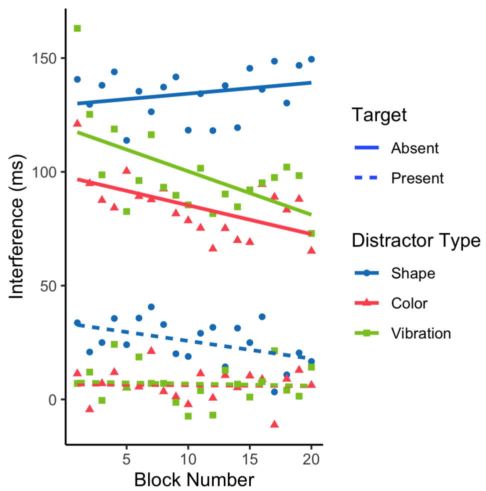


Figure A1 Distractor interference as a function of block number, separately for the Distractor Type (shape, color, vibration) × Target (present, absent) conditions.

Appendix 3. Target-distractor eccentricity and distance effects

When search items are arranged in an iso-eccentric display, distractor interference has been reported to decrease as the distance between the target and distractor increases (e.g., Gaspar and McDonald 2014). However, in our present design, the display items were arranged horizontally and equally split between the left and right sides, with both target eccentricity (5 eccentricities on one side) and distractor eccentricity (5 on the other side) varying randomly (though being equally likely) across trials. Accordingly, the distance of the distractor to the target varied, and this may have influenced distractor interference. To examine this, we used the target-only (TO) condition as the baseline against which we calculated the distractor interference on target-plus-distractor (TD) trials. Figure A2 shows the heatmap of the target-distractor interference.

As can be seen, distractor interference decreased generally, but not always, with increasing target-distractor distance. When the target was presented at the most central (i.e., the thumb and index-finger) locations, interference roughly followed a decreasing function (though there was an ‘odd-one-out’, 10-ms facilitation effect when both the target and the distractor appeared at the thumb positions). In contrast, when the target was presented at the (most peripheral) pinky-finger position, interference was most marked when the distractor appeared at the (most central) thumb position (a distance of 5, the shortest distance for this target location) and then decreased as the distance increased (from 5 to 9, though with an ‘odd-one-out’ reversal at distance of 10, when both the target and distractor appeared at the pinky-finger positions). Thus, the pattern of target-distractor distance seen with effects iso-eccentric ring-type item arrangements does not entirely generalize to horizontal arrangements, likely because the relative saliencies of the distractor and target – and, accordingly, their competitiveness for attentional selection – are eccentricity-dependent. In particular, a ‘central’ target at the thumb or index-finger position would be more salient than a ‘peripheral’ distractor at the pinky-finger location, and vice versa – explaining the general effect pattern seen in our design.

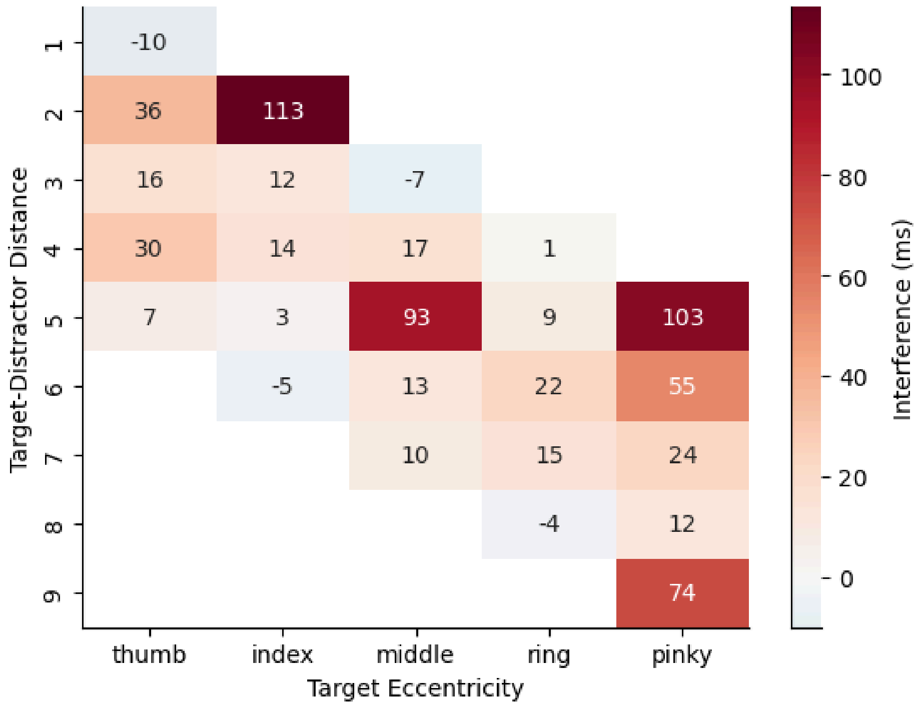
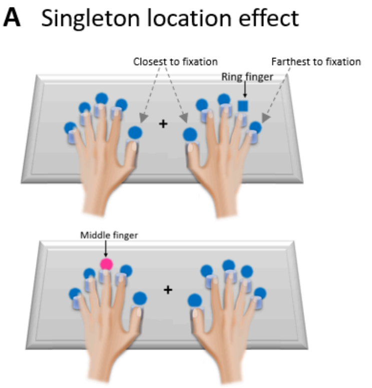


Figure A2 Heatmap of distractor interference (on TD trials, in ms). Rows indicate the target eccentricity (i.e., the locations of the fingers in our multi-modal setup), and columns the target-distractor distance. Given that the target and distractor were located on opposite sides, some distances are missing (because they were impossible) for a given target location.

To further look into how eccentricity affects the processing of singleton target or distractor items, we examined the mean RTs in the target-only (TO) and the distractor-only (DO) conditions as a function of the eccentricity of the respective singleton, for all Experiments (1, 2a, and 2b). Figure A3 provides an illustration of the variable eccentricities (A), a depiction of the effect patterns in Experiments 1, 2a, and 2b (C, D, E), and the results of the respective ANOVA tests. As can be seen, across all three experiments, the mean RTs were slower for the DO conditions vs. the TO condition (the main effect of the Singleton Type), and for the peripheral vs. the central Singleton Location. Interestingly, the mean RTs for the target-only condition increased (relatively) monotonically as the target eccentricity increased, whereas the three distractor-only conditions failed to show any eccentricity effect – which accounts for the significant interactions. The mean RTs for the fastest distractor-only conditions (DO-Color and DO-Vibration) were slower than (Experiment 1) or similar to (Experiment 2) to the slowest condition in the target-only condition (i.e., the target presented at the pinky-finger location). This suggests that in order to avoid overlooking the target (and commit a ‘target-miss’ error), participants tended to respond ‘target-absent’ (when there was no target in the display) only after sufficient time had elapsed that would have allowed even the ‘slowest target’ (had it been present) to be registered, that is: the waiting time on target-absent trials is set according to the distribution of task-relevant ‘target activity’ sampled on target-present trials. Note that this waiting time also depends on target prevalence: it appeared shorter in Experiments 2a and 2b (where the ratio of target-absent:present trials was 1:1) than in Experiment 1 (where the ratio was 2:1). Further, the elevated RT level in the DO-Shape condition (vs. the DO-Color and DO-Vibration conditions) reflects the additional time a shape target would have taken to be registered (had it been present) with a competing shape distractor target in the display.



B

RT	*df*	*F*	*p*	η_p^2	BF_{incl}
Experiment 1					
Singleton type	3, 60	137.079	< 0.001*	0.873	> 100
Eccentricity	4, 80	21.986	< 0.001*	0.524	> 100
Singleton type × Eccentricity	12, 240	15.771	< 0.001*	0.441	> 100
Experiment 2a					
Singleton type	2, 34	11.704	< 0.001*	0.408	> 100
Eccentricity	4, 68	10.266	< 0.001*	0.377	> 100
Singleton type × Eccentricity	8, 136	4.980	< 0.001*	0.227	> 100
Experiment 2b					
Singleton type	3, 51	57.797	< 0.001*	0.773	> 100
Eccentricity	4, 68	5.314	< 0.001*	0.238	> 100
Singleton type × Eccentricity	12, 204	5.674	< 0.001*	0.250	> 100

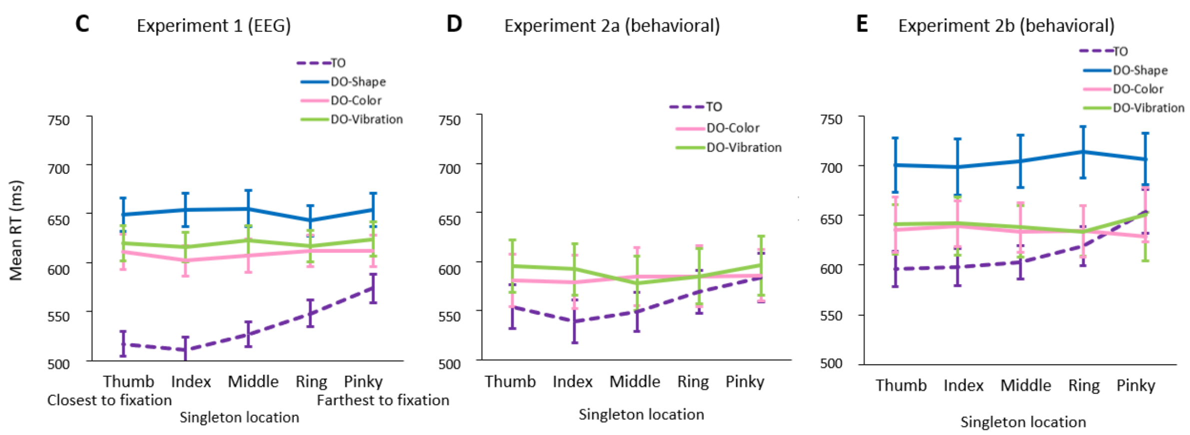


Figure A3 (A) Schematic illustration of the varying singleton locations. (B) The results of repeated-measures ANOVAs with the factors Singleton Type and Singleton Eccentricity. (C) Mean RT as a function of singleton eccentricity, separately for the target-only (TO) and the three different distractor-only conditions (DO-Shape, DO-Color, DO-Vibration), for Experiments 1, 2a, and 2b; the error bars represent one standard error.

Appendix 4. Summation analysis

To examine how attention was distributed between the target and the salient distractors, we calculated the additive (TD + DO) difference waves and compared them to the target-only (TO) condition (using a similar approach to, e.g., Gaspar and McDonald 2014; Liesefeld et al. 2017). Recall that the target-referenced and distractor-referenced ERLs involve the opposite subtractions. If attention is fully engaged with the singleton in the distractor-only or target-only conditions (DO, TO) but not in the target-distractor conditions (TD), the sum of the TD and DO ERLs would result in a waveform exceeding the target-only (TO) ERL. However, if the distractor was suppressed to the same degree due to general dimension- or modality-based down-weighting, attentional engagement by the distractor would be independent of the presence of a competing target. If this were true, the summation of the TD and DO ERLs would be near-equal to the TO condition in which the target fully engages attention. Figure A4 emphasizes the comparison between the baseline (TO) and each distractor-type condition. Figures A4-C, D, and E present the (contralateral minus ipsilateral) difference waves for the three types of distractor. As can be seen, the additive waves (TD + DO, red dashed lines) for each distractor condition nearly fell together with the target-only ERL waves (solid purple lines) for early components. The summed TD-Shape plus DO-Shape N2pc is similar to the TO condition (Figure A4-C) – indicating that the amount of the attentional resources engaged by the shape distractor and the target in the TD condition was similar to the total amount of resources engaged by the target in the TO condition. The cross-dimension and cross-modality conditions show a similar, additive N2pc pattern (see Figures A4-D and E). This suggests that the differential N2pc amplitudes observed in the distractor-present conditions was a consequence of the power of the distractor to summon attentional resources: the intra-dimension engaged roughly half the attentional resource, while the color and vibrotactile distractors did not significantly redistribute attention.

As can be seen from Figure A4-E, the vibrotactile distractor elicited strong ERP components in the sensorimotor area (CCP and CCN from C3/C4), and the large voltages spread to the parietal-occipital area (PO7/PO8). Both the CCP and CCN were elicited by the high-frequency distractor vibrations; their positive/negative values are simply owing to the different reference locations: the target or, respectively, the distractor side (see Figure A4-B). The summation of the TD-Vibration plus DO-Vibration waveforms was very close to the waveform of the target-only condition (TO), CCN and CCP reflects sensorimotor activity solely driven by the salient vibrotactile distractor.

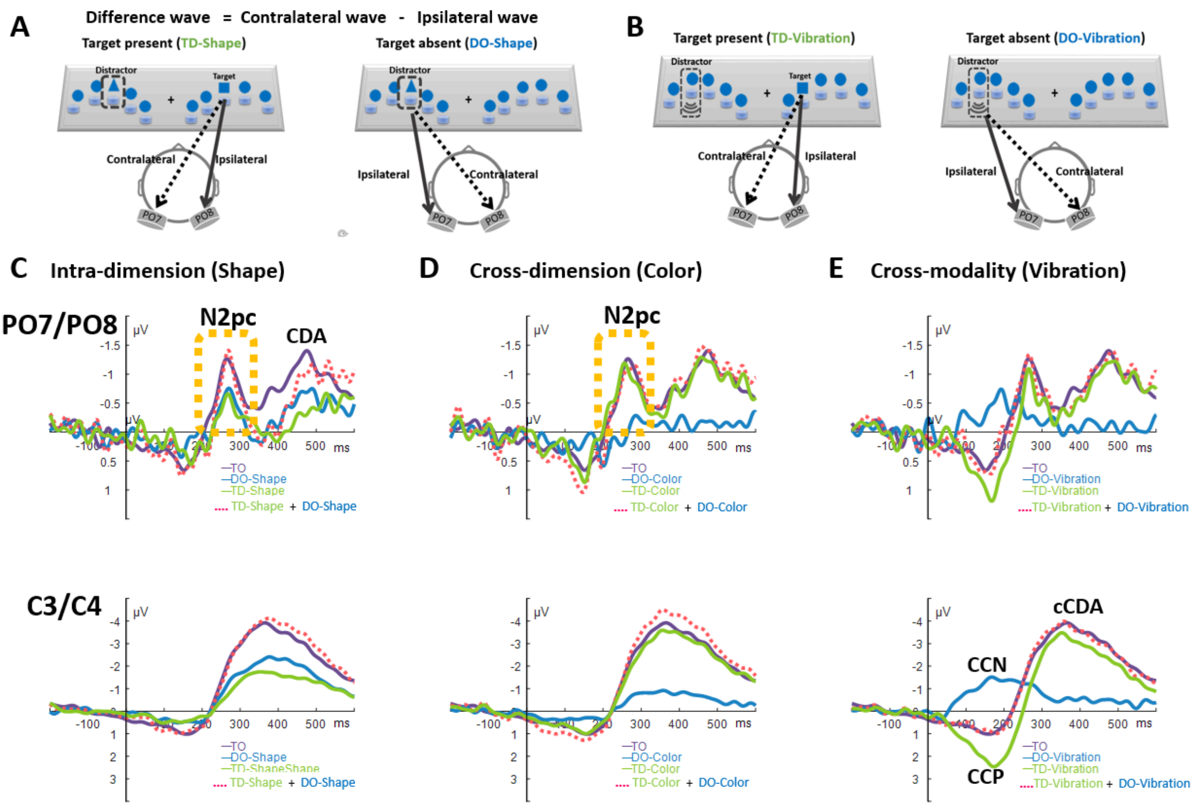


Figure A4 (A) and (B) Illustration of stimulus constellations contra- and ipsilateral to the target location on target-present (TD) trials and, respectively, the distractor location on the target-absent (DO) trials, for the intra-dimension (Shape) distractor condition (A) and the cross-modality (Vibration) distractor condition. (C), (D), and (E) Contralateral minus ipsilateral differences waves from electrode pairs PO7/PO8 (panels in upper row) and C3/C4 (panels in lower row), separately for the three distractor-type conditions (columns). The red dashed lines represent the summed TD + DO waves for each distractor condition, and the solid purple lines the TO waves. As can be seen, the summed waves are near-overlapping with the target-only wave.

Chapter 3: Salient Stimuli-driven Distractors Capture Attention without Engagement: A Cross-modal EEG Study

Salient stimuli-driven distractors capture attention without engagement: A cross-modal EEG study

Shao-Yang Tsai, Jan Nasemann, Hermann Müller and Zhuanghua Shi

Ludwig-Maximilians-Universität München, 80802 München, Germany

Author Note

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Abstract

The handling of task-irrelevant distractors and the underlying mechanisms involved have been debated. This study investigated how spatial and feature-based attentional templates influence distractor handling using EEG within a variant Eriksen Flanker paradigm. Participants were instructed to focus on a blue triangle target and respond to its orientation, either on the middle line or in the lateral regions, while ignoring various distractors that varied within the same dimension as the target, across different dimensions, or across different modalities. Behavioral results revealed that distractors sharing the same target features caused the most interference, more so than those different in dimension or modality. The N2pc amplitude suggested increased attentional engagement towards lateral distractors or targets, particularly when the distractor shared more features with the target, thereby intensifying interference effects. Meanwhile, cross-modality distractors elicited a distinct central contralateral negativity (CCN) without affecting search performance. CCN and positive posterior contralateral (Ppc) components indicated early sensory registration of lateralized distractors, ruling out Ppc as indicative of early distractor suppression. Findings support the 'down-weighting' hypothesis, showing that distractors can be registered without further engagement. The spatial template acted as "distractor location shielding" rather than "target location enhancement," as reflected by the N2pc component. This research implies that effective distractor handling through shielding distractors' locations and down-weighting approaches may render proactive or reactive suppression mechanisms, typically reflected by the P_D component, unnecessary.

Keywords: Distractor suppression, attentional engagement, N2pc, P_D, CCN.

Introduction

Effective attentional control is crucial in our daily lives, especially when we encounter conflicting stimuli. The classic Eriksen Flanker Task (Eriksen & Eriksen, 1974) illustrates this by requiring participants to respond to central stimuli while ignoring adjacent distractors. This task has shown that incongruent flankers (e.g., "< < > < <", where the response targets the direction of the central arrow) can significantly delay responses compared to congruent (e.g., "> > > > >") or neutral conditions (e.g., "- - > - -"). The flanker effect highlights the difficulties in suppressing adjacent irrelevant information and resolving conflicts, despite the target location is known beforehand (Buetti et al., 2014; Eriksen & Eriksen, 1974; Gratton et al., 1992; Lavie et al., 2004; Van Veen & Carter, 2002). In visual search, similarly, salient distractors can capture attention, causing distractor interference (Theeuwes, 1992; Wolfe, 1994, 2021). This raises the question of how we can effectively avoid interference from distractors?

Spatial shielding may prioritize specific locations, enhancing stimulus processing in those areas. However, as demonstrated in Flanker tasks, when distractors are positioned close to the target, this spatial shielding can become ineffective (Buetti et al., 2014; Eriksen & Eriksen, 1974; Lavie et al., 2004). In scenarios where the locations of targets and distractors are unpredictable, down-weighting features or dimensions of distractors while up-weighting those of the target can aid in shielding against distractors (Goschy et al., 2014; Liesefeld & Müller, 2019, 2021; Sauter et al., 2018; Zhang et al., 2019). When the distractor is singled out in a dimension or modality that is not target-defining, the weight of this dimension or modality can be down-modulated in the computation of attentional priorities without impeding target selection. According to these accounts (DWA, Found & Müller, 1996; Liesefeld & Müller, 2019; Müller et al., 2003; Nasemann et al., 2023; MWA, Töllner et al., 2009), top-down control increases the weight of the search-critical target dimension, or modality, while simultaneously decreasing the weight of potential distractor dimensions, or modalities. This down-modulation reduces the weight of distractor signals in the computation of search priorities, making them less likely to capture attention. However, it remains unclear regarding the effectiveness of this differential up-/down-weighting in relation to target-distractor similarity in terms of stimulus features/dimensions/modalities and its interaction with target locations.

To investigate how attention allocation is influenced by target-distractor relations, we modified a search task to include a predefined target region and varied the features, dimensions, and modalities of the distractor. During this task, we recorded EEG to capture key event-related potentials (ERPs) associated with lateralized spatial attention. Notably, the N2pc component (negativity posterior contralateral, also referred to as PCN) is a negative-going potential observed in the posterior central electrodes contralateral to the attended side, appearing between 200-350 ms after stimulus onset (Duncan et al., 2023; Hickey et al., 2009). It is thought to reflect the allocation of attention to a lateralized display item (e.g., Eimer, 1996; Luck, 2011; Luck & Hillyard, 1994; Sawaki & Luck, 2010, 2014; Töllner et al., 2012; Woodman & Luck, 1999, 2003). Recently, Zivony et al. (2018), however, suggested that the N2pc represents the 'engagement' of attention by an item (rather than attentional orienting as such), providing a crucial measure of a distractor's ability to engage attentional processing resources (i.e., 'capture attention'). In related findings, the Ppc (Positivity posterior contralateral), the P_D (Distractor Positivity), and the CDA (Contralateral Delay Activity) are also linked to lateralized selective attention. The CDA component, which appears about 250 ms post-stimulus onset, indicates the registration of lateral stimuli (both distractor and target) in working memory (Chen et al., 2022; Eimer et al., 2004; Eimer & Driver, 2000; Forster et al., 2016; Töllner et al., 2009). Additionally, the Ppc and P_D components, observable within 100–200 ms post-stimulus, are believed to reflect early sensory processing or rapid distractor suppression (e.g., Itthipuripat et al., 2014; Gaspelin & Luck, 2018a), though its role remains controversial. In addition, standard N2 and P3 components are linked to conflict detection and cognitive control, such as flanker tasks where the target appears at the central (for reviews, see Folstein & Van Petten, 2008; Polich, 2007).

Study Design Rationale

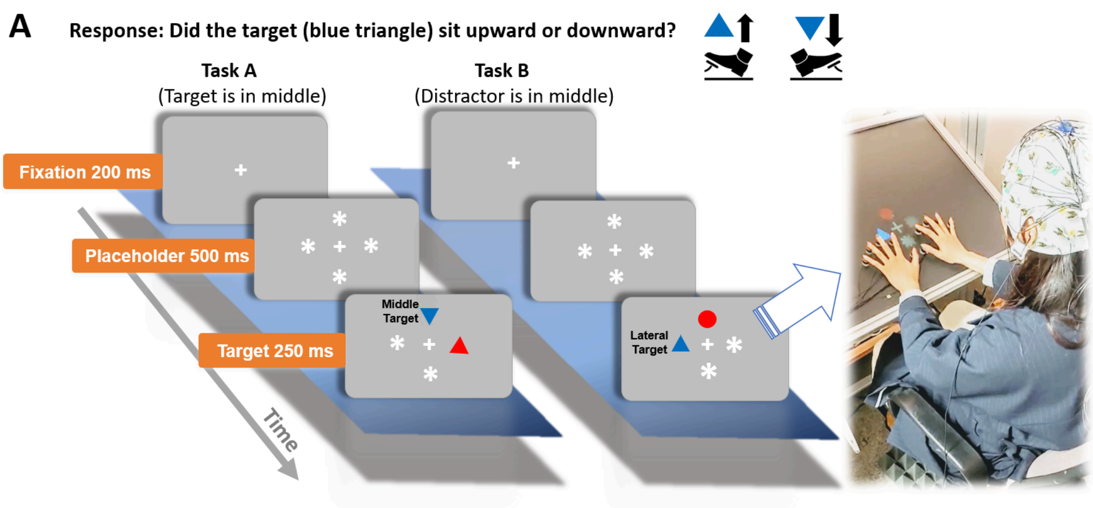
In this study, we predefined the target regions (Task A: the target at central region, and the distractor lateralized; Task B: the target at lateral regions, and the distractor at the central region, see Figure 1A) to mirror aspects of the Eriksen Flanker task, where the target position is fixed and, 'flanking' items not occupying the target position (Eriksen & Eriksen, 1974). This setup contrasts with traditional multi-item search tasks where the location of the target location is unknown. Our design allowed us to examine the extent to which distractors of the various types interfere with or capture attention, even when participants knew beforehand which positions to ignore as potential distractor locations and which to focus on as they contain the response-relevant target. Additionally, we varied the features, dimensions, and modalities of the distractors, which were randomly mixed across trials.

Based on prior research (Gaspar & McDonald, 2014; Tsai et al., 2023), it's reasonable to suggest that the total attentional resources allocated to both the target and distractor are relatively fixed, which can be observed through N2pc amplitudes. Assuming that the N2pc amplitude in a lateralized target-only condition represents the full allocation of available resources, we propose that spatial templates may adjust this distribution, favoring the target location while potentially reducing attention to the distractor location when the distractor presents. Under this framework, three possible mechanisms can be distinguished with the condition of the target and distractor share the same features (i.e., two items shared the same feature as the target-only item):

1. **Distractor Location Shielding Only**: If the distractor location in Task A is effectively down-modulated, we expect to see an N2pc amplitude significantly lower than half of that observed in the target-only condition, indicating a reduction in resources allocated to the distractor location. This hypothesis does not assume any enhancement at the target location.
2. **Distractor Location Shielding and Target Location Enhancement**: This predicts a combination of down-modulation at the distractor's location and up-modulation at the target's location. The N2pc amplitude for the SF condition in Task A would be smaller than half the amplitude from the target-only condition, while in Task B, the amplitude would exceed this halved benchmark.
3. **Target Location Enhancement Only**: If there's an enhancement (i.e., up-modulation) at the target's location, the N2pc amplitude for the SF condition in Task B would be significantly larger than half the target-only condition's amplitude, showing increased attention at the target's location. Conversely, the N2pc amplitude for the SF condition in Task A would be similar to half the target-only amplitude, indicating no suppression at the distractor location.

It should be noted that the above hypotheses only consider the the spatial attentional allocation. However, considering target-distractor similarity and the Dimension Weighting and Modality Weighting Accounts (Found & Müller, 1996; Liesefeld & Müller, 2019; Müller et al., 2003; Töllner et al., 2009), attentional control dynamically adjusts feature weights to enhance target recognition and suppress distractors, affecting attention capture and processing efficiency. Differentiating between enhancing target features and down-weighting of distractor features remains a challenge du to the ambiguity in total resource allocation (Liesefeld & Müller, 2021). Moreover, active suppression typically shows activity below baseline levels (Gaspelin et al., 2023; Liesefeld et al., 2023), while what seems like passive down-weighting could stem from limited remaining resource after other cognitive processes have consumed significant resources. Our study uses ERL indexes to investigate how distractor-target similarity modulate attention. Our hypotheses explore how feature templates influence attentional modulation (see illustration in Figure 1D):

1. **Distractor Down-Weighting:** If distractors are actively down-weighted, Participants would not engage with distractors that lack target features. This would be indicated by the absence or smaller amplitude of N2pc for such distractors. Notably, the P_D component is expected to be absent. Conversely, distractors resembling the target features are predicted to elicit substantial N2pc amplitudes, signifying attentional engagement.
2. **Proactive Suppression:** This hypothesis suggests that participants proactively suppress any distractor at known locations, which should be reflected by the presence of a P_D component with no corresponding N2pc.
3. **Reactive (passive) Suppression:** This hypothesis proposes that the system preferentially enhances target-related features (i.e., target features are up-weighted). Distractors with target features will elicit an N2pc, signifying engagement, followed by a P_D component if this engagement is deemed inappropriate, indicating reactive suppression.



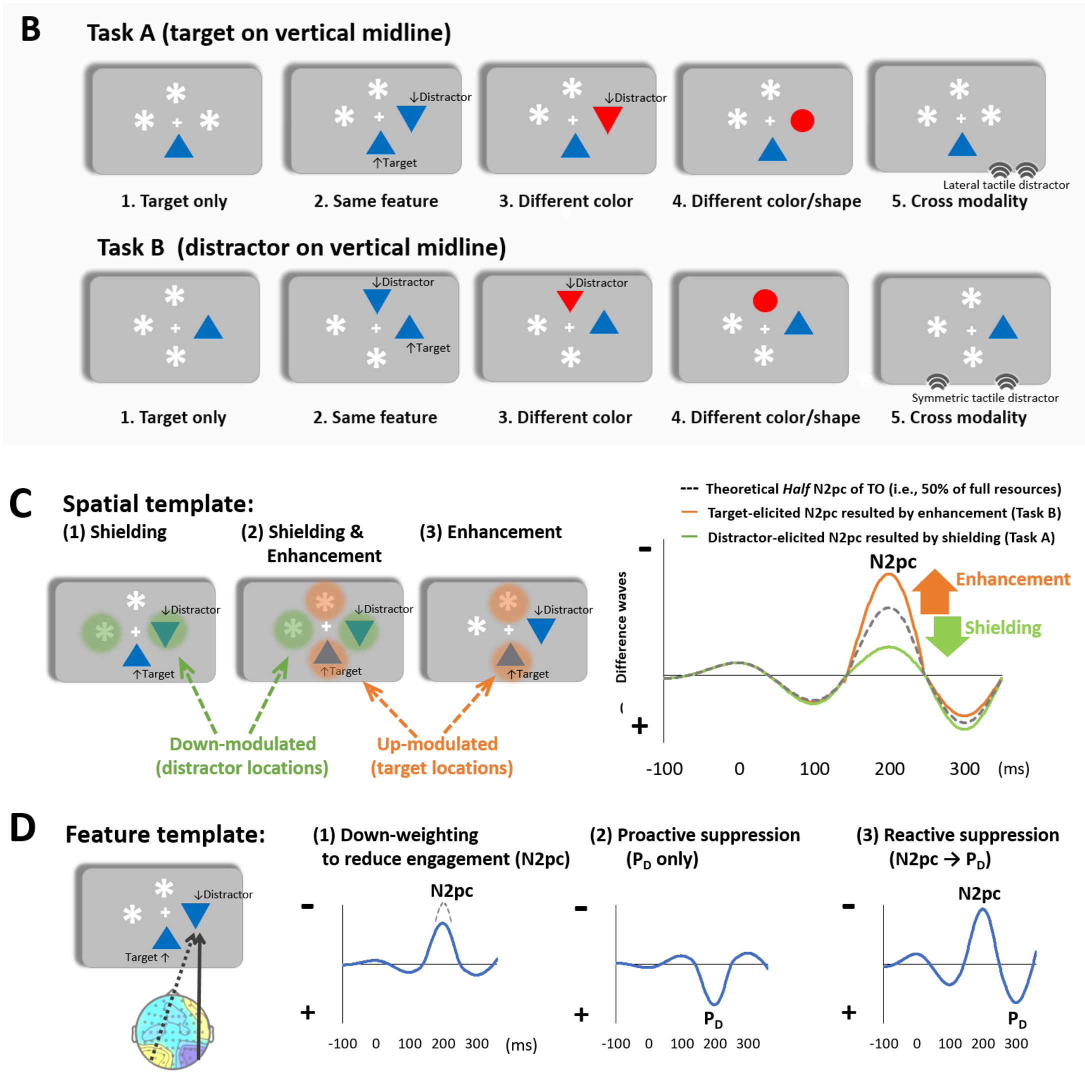


Figure 1. The schematic illustration of the experiment. **A.** Participants sat on a chair and placed their fingers on ten tactile vibrators (solenoids). Visual stimuli were presented just above the solenoids. The response-critical 'target' item was consistently a blue triangle: participants had to indicate the target's pointing direction (up- vs downwards) using foot pedals. There were two (blocked and counterbalanced) task conditions: in the task A, the response-critical target item was invariably presented (at the top or bottom position) on the vertical midline (so the distractor appeared laterally); conversely, in the task B, the target was consistently presented (at the left or right position) on the horizontal midline (so the distractor appeared at a vertical-midline position). **B.** In both tasks (A and B), there were five conditions: (i) target-only (TO), same-feature (SF) distractor, (iii) different-color (DC) distractor, (iv) different-color and different-shape (DCS) distractor and (v) cross-modal (CM) distractor. **C.** The hypothetical effects of spatial templates on attention allocation exemplified by Task A, which features a central target and a peripheral distractor. The dashed

line denotes the theoretical Half-Distribution Baseline of TO N2pc, a hypothetical even distribution of attentional resources between the target (50%) and distractor (50%). The colored lines indicate modifications in N2pc amplitude due to spatial templating: the orange line represents an 'Enhancement' effect, signifying an up-modulation of attention at the target location, while the green line signifies 'Shielding,' or a down-modulation of attention at the distractor location. **D.** Depicts the influence of feature templates on attentional modulation in Task A. The hypothetical responses are illustrated for three conditions under feature-based attentional manipulation: (1) 'Down-weighting' hypothesizes a reduced engagement with distractors, reflected in a decrease in N2pc amplitude. (2) 'Proactive suppression' suggests that known distractor locations will be actively suppressed, resulting in the presence of P_D without accompanying N2pc, signifying an absence of attentional engagement. (3) 'Reactive suppression' posits that distractors sharing target features will initially attract attention, shown by an N2pc, but subsequently, if deemed inappropriate, this engagement will be followed by a P_D component, indicating a reactive suppression or disengagement from the distractor.

Method

Participants

Valid data sets were obtained from 21 participants (6 female, 15 male), with an average age of 27 years (standard deviation, SD: 2.5 years; age range: 23 to 33 years), out of 29 participants recruited for the study[12]. All participants were right-handed, and none had a history of a neurological or psychiatric disorder. They were compensated for their service at a rate of 9 Euros per hour. The sample size was determined based on previous studies investigating cross-modal attention (Tsai et al., 2023; Nasemann et al., 2023; Chen et al., 2022; Chen et al., 2021), which exhibited medium-to-large effect sizes. Using similar effect sizes, G*Power analysis (Faul et al., 2007) recommended a minimum of 20 participants. The study was approved by the Ethics Board of the Psychology and Educational Sciences at LMU Munich. Participants provided written informed consent prior to the formal experiment.

[12] A total of 29 participants were initially recruited, of which, however, eight had to be excluded: one owing to an amplifier-battery failure during EEG recording and seven due to excessive EEG artifacts.

Apparatus, stimuli, and tasks

The experiment was implemented using MATLAB (v.2012) with the Psychtoolbox v. 3.08. The setup is illustrated in Figure 1A. Visual displays were projected on a semi-transparent plexiglas table using a rear projector (window size: 38.1° × 12.5°), with the table tilted at an angle of 60° towards the participant. Vibrotactile stimuli were delivered to the tips of the participant's fingers via ten solenoid actuators (Dancer Design; each 1.8 cm in diameter) positioned near the bottom, the left, and the right of the visual items. Participants responded by pressing one or the other of two foot pedals.

Two types of task were introduced to examine how the brain shields processing of the response-critical target from the potentially interfering effects of a single, irrelevant distractor that shared more or less features with the target. In the task A, the target was consistently located at a position on the vertical midline, either above or below the central fixation marker, while the distractor (on distractor-present trials) appeared at a position on the horizontal midline, either to the left or the right of fixation. In the task B, the placements of the target and distractor were reversed: the target appeared at a lateral (left/right) position and the distractor at a top/bottom position (see Figure 1A). Thus, there were only four possible stimulus locations (left/right and top/bottom; eccentricity of 5.2° of visual angle with respect to central fixation), one of which was occupied by the target and the other by the distractor (on distractor-present trials); the other two positions were occupied by a placeholder star (*), to balance the low-level sensory inputs between the left and right and the top and bottom of the displays. The items subtended 4.2° of visual angle. Their color was either blue, red, or gray, with the same luminance (36 cd/m²).

During the task, both visual and tactile stimuli were presented at the same time. Participants placed their fingers on the top of the solenoids. As illustrated in Figure 1A, the 'thumb' solenoids were positioned near the bottom visual item, and the 'index-finger' solenoids near the left and right visual items, respectively – ensuring that the vibrotactile (solenoid /finger) setup did not obscure the visual stimuli projected onto the (plexiglas) screen surface. The tactile vibrations were of either 40 Hz or 100 Hz. We used the 100-Hz vibration as the distractor signal and 40-Hz vibrations as background signals (delivered to the non-distractor fingers), similar to our prior studies (Tsai et al., 2022; Nasemann et al., 2022). Note that on target-only trials as well as trials with a target plus a visual distractor (see below), all ten fingers were stimulated uniformly at 40 Hz. To block out any noise from the vibrations, participants wore headphones (a Philips brand with a 30-mm speaker drive) that played pink noise at 65 dBA during the task.

Figure 1B illustrates the five stimulus conditions: (i) the target-only (TO) baseline condition without a distractor; the target was a blue triangle pointing either up- or downward, with the task requiring participants to respond to the target's pointing direction; (ii) the same-feature distractor (SF) condition with a blue triangle as a distractor; (iii) the different-color distractor (DC) condition with a red triangle as a distractor; (iv) the different-color and different-shape distractor (DCS) condition, with a red circle as a distractor; and (v) the cross-modal distractor (CM) condition, with vibrotactile distractors. When the distractor was the same shape as the target, namely, a triangle, its pointing direction was always opposite to that of the target.

In Task A, the visual distractor appeared on the left or right (and the target on one of the vertical midline positions). For the vibrotactile distractor, 100-Hz vibrations were delivered to the index, middle, ring, and little finger of either the left or the right hand, while the analogous fingers of the respectively other hand were stimulated at 40-Hz. In Task B, the visual distractor appeared at the top or bottom position on the vertical midline (and the target at one of the lateral positions). The 100-Hz 'distractor' vibrations were delivered to both thumbs, while all other fingers were stimulated at 40-Hz. The symmetric vibrotactile distractor stimuli thus 'highlighted' the vertical midline (though consistently the bottom position and never the top position).[13]

Design and procedure

Participants completed two tasks, labeled Task A and Task B, in a quiet, dimly lit laboratory room. Priori to the start of each task, they performed 20 practice trials to familiarize themselves with the particular task conditions and achieve a response-accuracy level above 80%.[14] Each task consisted of six blocks, each of 100 trials, yielding a total of 600 trials per task. After the 34th and 68th trial in each block, participants took a short break, and a longer break at the end of each block. The order of the tasks (AB vs. BA) was counterbalanced across participants. Within each block, the five basic conditions (TO, SF, DC, DCS, and CM) were presented in randomized order, with an equal number of trials per condition. Each task took approximately 35 minutes to complete.

The general procedure resembled that in similar studies of cross-modal processing

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[13] Note that, given the constraints imposed by the shape of the hands, balancing of the top and bottom positions was not possible.

[14] Those who scored below 80% underwent another 20 trials of practice. All participants passed the accuracy criterion within two blocks of practice.

from our lab (Tsai et al., 2022; Nasemann et al., 2022; Chen et al., 2022; Chen et al., 2021). Participants sat comfortably in front of the visuo-tactile display surface, with their fingers gently resting on the solenoid actuators (as shown in Figure 1A). The distance of the eyes to the central fixation marker was approximately 55 cm.

Each trial began with the fixation cross appearing in the display center for 200 ms, followed by a 500-ms placeholder display of four asterisks marking the four possible locations where the target and distractor could appear. The target and (on distractor-present trials) the distractor were then presented for 250 ms, followed by a blank screen. The tactile stimulation was synchronized with the visual target display, sharing the same onset and offset. The two possible target locations were fixed per task. Participants had to respond to the target triangle's pointing direction (the triangle pointing up- or down-ward) by stepping on the respective foot pedal (with the up-/downward pointing direction to left/right foot-pedal assignment counterbalanced across participants). The next trial started automatically after a randomized interval of 950–1050 ms.

Figure 1A illustrates an example of Task A (target at a vertical midline position) and one of Task B (target at a lateral position). In both tasks, the response-critical target item was a blue triangle, as indicated in the verbal instruction given prior to the experiment and the screen instruction at the beginning of each block. Participants were asked to respond to the target's pointing direction (up- or downward) as quickly and accurately as possible. In Task A, participants were instructed to consistently search for and respond to the blue triangle target on the vertical midline, while in Task B they were told that the target would consistently appear at one of the lateral positions. Participants were also instructed to maintain fixation on the central fixation marker and not to move their eyes during the experimental trials.

EEG recording and preprocessing

EEG signals were recorded continuously using 64 Ag/AgCl active electrodes (acti-CAP system; Brain Products Munich) connected to a BrainAmp Standard amplifier. The EEG signals were sampled at 1000 Hz and recorded per the international 10-20 system, with an active reference located at Fcz. The EEG data were preprocessed using EEGLAB v2020 (Delorme & Makeig, 2004). The EEG data were re-referenced offline to the mastoid channels (TP9 and TP10) during the preprocessing stage. Independent component analysis (ICA, extended infomax, Bell & Sejnowski, 1995; Lee et al., 1999) was employed to detect and remove artifacts caused by vertical and horizontal eye movements (blinks and saccades). Following artifact removal, the EEG data were filtered with a high-pass filter (1 Hz) and a low-pass filter (cut-off frequency 25 Hz). The data were then segmented into epochs of 1000 ms, referenced to the stimulus (target/distractor) onset, with a mean baseline correction (-200 to 0 ms) applied to every trial.

Electrodes PO7, PO8, C3, C4, Fz, Cz, and Pz were selected for further analysis, as we were interested in the event-related lateralizations induced by the lateral visual and tactile stimuli. Trials were 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. Seven participants were excluded from further analysis because more than 33% of the trials in one condition were rejected based on these criteria (one further participant was excluded due to a technical problem with EEG recording; see footnote 1). For the remaining data sets (N = 21), the average ‘bad-trial’ rejection rate was 9.1% for Task A and 7.2% for Task B. After excluding such trials, we submitted correct response-trials to further ERP analysis.

Statistical analysis

JASP (2021, version 0.16.4.0) was used for statistical analyses of the behavioral and ERP (event-related potential) data. Repeated measure ANOVAs were performed, and in cases in which the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied. Subsequently, if necessary, post-hoc multiple comparisons were performed Holm tests.

While participants were instructed to prioritize both response speed and accuracy, their reaction times (RTs) served as the primary behavioral measure. To ensure integrity of the RT data for the (subsequent) analyses of the ERPs and ERLs (event-related lateralizations), we implemented a specific inclusion criterion (the same we had applied in previous studies: (Nasemann et al., 2023; Tsai et al., 2023): we included only correct-response trials with RTs ranging between 250 ms and 1000 ms, which roughly corresponded to two standard deviations (SDs) of the mean. Applying this criterion, the maximum rejection rate among the subjects was 4%.

ERLs were calculated by referencing the contralateral and ipsilateral waves to the EEG electrodes to either the distractor location (Task A) or the target location (Task B), resulting in the respective – contralateral minus ipsilateral – ‘difference waves’. The N2pc, Ppc, and CDA components were obtained from the parieto-occipital electrodes (PO7/PO8), and the CCN component was calculated from the medial central electrodes (C3/C4). Following the standard approach established by Luck (2005), we employed the mean-amplitude method, that is, we calculated the mean amplitude over a predefined time window. The time windows for each component were determined based on the selection of their respective peak time points. Of note, the observed peak times showed a difference between Tasks A and B: the peaks occurred somewhat earlier in Task B (with the lateralized target) vs. Task A (with the lateralized distractor). For the distractor-elicited ERLs in Task A, we averaged the amplitudes within the respective time windows (Dodwell et al., 2021; Nasemann et al., 2023; Qiu et al., 2023; Tsai et al., 2023): 110–160 ms for the Ppc/early P_D, 170–230 ms for the N2pc, 50–250 ms for the CCN, and 340–400 ms for the CDA. For the target-elicited ERLs in Task B, adopting a data-driven approach, we adjusted the time windows slightly earlier according to the peak time of each component: 90–140 ms for the Ppc, 150–210 ms for the N2pc, 50-250 ms for the CCN, and 280–400 ms for the CDA.

For each ERL component, a repeated-measures ANOVA was performed with the single factor Distractor Type. Note that in the TO (target-only) condition of Task A, because the target appeared on the vertical midline and there were no lateral distractors, there was no lateralization wave (ideally, the difference wave should be 0 μV). Thus, for the TO condition to provide a baseline for the four Distractor-Type conditions (each with a lateral distractor), we randomly selected 50% of the TO trials as having a "pseudo-distractor" on the left side, and the other 50% as having one on the right side. The purpose of this was to calculate the difference waves (contralateral minus ipsilateral) for comparison only. As expected, the difference wave in the TO condition of Task A (with the target on the vertical midline) was almost a flat line, very close to 0 μV.

Results

Behavioral results

Figure 2A shows the average correct RTs. A two-way repeated-measures ANOVA with the factors Task (A, B) and Distractor Type (TO, SF, DC, DCS, CM) revealed a significant main effect of Distractor Type, $F(4, 80) = 56.088$, $p < .001$, $\eta_p^2 = 0.737$, but not of Task, $F(1, 20) = 2.648$, $p = .119$, $\eta_p^2 = 0.117$, though numerically RTs were slower in Task B (with the lateral target) than in the Task A (with the vertical-midline target). The interaction between Task and Distractor Type was non-significant, $F(4, 80) = 2.014$, $p = .100$, $\eta_p^2 = 0.092$. Post-hoc tests for Distractor Type revealed RTs to be the slowest in the same-feature (SF) distractor condition, that is, significantly slower than in all other conditions (RT difference relative to TO: 26 ms, $p < .001$; relative to DC: 20 ms, $p < .001$; relative to DCS: 27 ms, $p < .001$; and relative to CM: 29 ms, $p < .001$). Further, while response speed in the DCS and CM conditions did not differ from that in the TO condition (*p*s > .32), RTs in the DC condition were marginally slower compared to the TO baseline ($p = .060$; uncorrected $p = .015$). This pattern indicates that the presence of cross-dimensional and cross-modal distractors generally did not interfere significantly with task performance, though there appeared to be a slight (statistically marginal) cost with DC distractors (which shared the same triangle shape, but not the color of the target). Although the distractors in the DC and DCS conditions shared the same color (while having different shapes), there remained a slight but significant difference, of 7 ms, in the mean RTs between these two conditions ($p < .01$). The 9-ms difference of the DC vs. the CM condition was also significant ($p < .01$). Thus, while the magnitude of distractor interference gradually decreased as the distractors shared fewer (visual) features with the target (i.e., SF > DC > DCS = CM), robust interference was observed only in the SF condition; there was some marginal interference in the DC condition, whereas there was no interference (relative to the TO baseline) in the DCS and CM conditions.

Figure 2B illustrates the average response accuracy in the five (TO, SF, DC, DCS, CM) conditions. The two-way repeated-measures ANOVA analysis revealed no impact of task on the mean error rate ($F(1,20) = 1.276$, $p = .272$, $\eta_p^2 = .06$), and no interaction between Task and Distractor Type ($F(4, 80) = 0.412$, $p = .800$, $\eta_p^2 = .02$). However, the main effect of Distractor Type was significant ($F(4,80) = 4.128$, $p = .012$, $\eta_p^2 = .171$), largely owing to a slightly increased error rate in the SF condition.

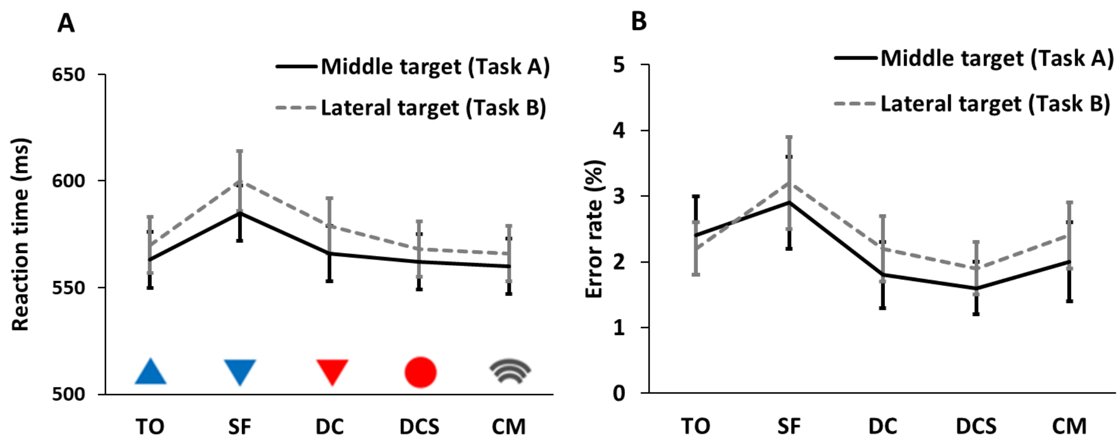

Figure 2. Mean reaction times (A) and accuracy (B) for the two tasks (Task A: target on vertical midline; Task B: target at lateral position), as a function of the Distractor Type: target-only (i.e., no-distractor) condition (TO), same-feature (SF)distractor condition; different-color (DC) distractor condition; different-color and different-shape (DCS) distractor condition; a cross-modal (i.e., vibrotactile) (CM) distractor condition. Error bars represent the standard error of the mean.

ERP results

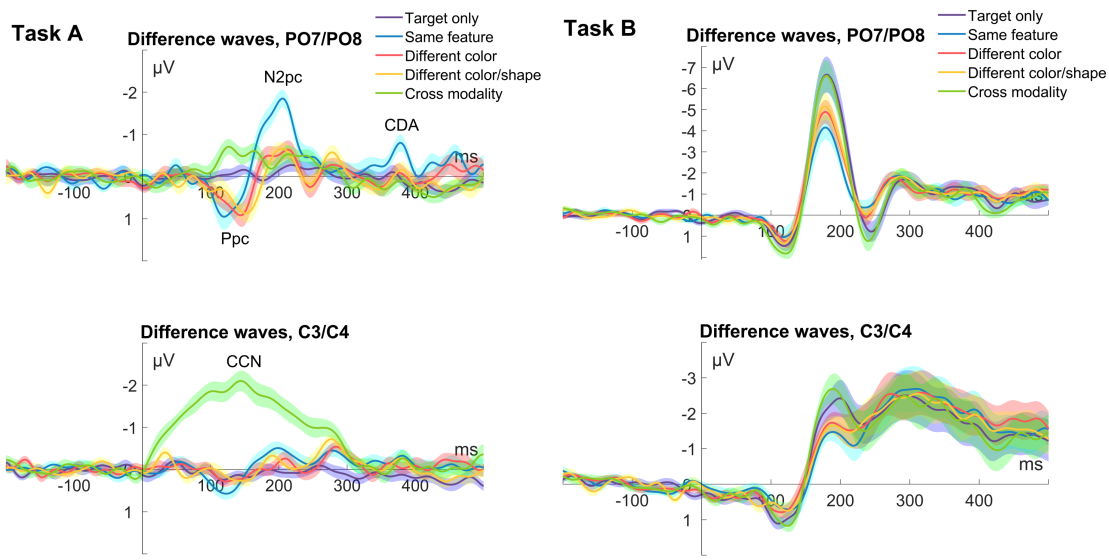

Figure 3. ERL (contra- minus ipsilateral) waveforms from PO7/PO8 (upper panels) and C3/C4 (lower panels). The shaded area enveloping each waveform is the standard error of the mean.

Our ERP analyses focused on event-related lateralizations (ERLs), that is, the difference waves between the contralateral and ipsilateral responses to lateral distractors in Task A and, respectively, lateral targets in Task B (see Figure S1) for the various components of interest. The Ppc, N2pc, CDA, and CCN components for the various distractor types from PO7/PO8 and C3/C4 are depicted in Figure 3. There was no late P_D component in the present experiment (see upper left panel of Figure 3). As either the distractor (Task A) or the target (Task B) was presented lateralized, the distractor- and target-related ERL results are presented in separate sections for the two tasks below. Any 'conflict' effects between the (incongruent) triangle distractors and the target, indicated by the N2 and P3 ERP components typically seen in flanker or stop-signal tasks, will be reported in the final section of the ERP analysis.

Task A (Vertical-midline target/lateral distractor): distractor-elicited lateralizations

Distractor-elicited Ppc (110–160 ms). As indicated by simple t-tests, the Ppc amplitudes were significantly greater than zero in the SF (p = .011), DC (p = .002), and DCS (p = .002) conditions. No significant Ppc amplitudes were observed in the TO (p = .857) and CM (p = .998) conditions. A one-way repeated-measures ANOVA of the Ppc amplitude revealed a significant Distractor-Type effect, $F(4, 80) = 13.234$, $p < .001$, $\eta_p^2 = 0.398$. The Ppc mean amplitude was larger in the SF, DC, and DCS conditions compared to the TO baseline condition (mean differences of 0.717, 0.937, and 0.679, respectively; ps = .063, .011, and .002, respectively). The CM condition exhibited significantly more negative amplitudes than the SF, DC, DCS, and TO conditions (mean differences of 1.193, 1.269, 1.154, and 0.476, respectively; ps = .003, .001, < .001, and .047, respectively), likely attributable to the spread of negative voltages elicited by tactile sensation from the sensorimotor area (see CCN section below). However, there were no significant differences among the three lateral visual distractors (SF, DC, and DCS; $F(2, 40) = 0.205$, $p = .816$, BF = 0.153), indicating that the different types of visual distractor elicited comparable amplitudes of Ppc.

Distractor-elicited N2pc (170–230 ms). There was a strong distractor-elicited N2pc in the SF distractor condition, compared to all other conditions (Figure 4 B). The one-way repeated-measures ANOVA yielded a significant Distractor-Type effect, $F(4, 80) = 13.706$, $p < .001$, and $\eta_p^2 = 0.407$. Post-hoc Holm-corrected tests confirmed that this effect was caused by the SF distractor (comparisons to the other four conditions: mean differences > 0.93, ps < .009), while there were no differences among the other four conditions (mean differences < 0.14, ps >.369). These results suggest that only the same-feature (SF) distractor, sharing both the triangle shape and the color with the target, engaged significant attentional processing, whereas none of the other distractors – including the different-color (DC) distractor, which shared the same triangle shape with the target, but not the color – caused reliable distraction (above the TO baseline). The fact that the different-color distractor was handled similarly to the different-color different-shape (DCS) distractor is theoretically interesting, suggesting that both types of distractor were filtered out by their (red) color. This pattern is consistent with the dimension-weighting account (DWA, Found & Müller, 1996; Liesefeld & Müller, 2019; Müller et al., 2003), according to which intra-dimension distractors (sharing the search-critical target dimension) are hard to suppress, whereas cross-dimension distractors (defined in a non-critical dimension) can be effectively filtered out via top-down dimensional set.

Distractor-elicited CDA (340–400 ms). A one-way repeated-measures ANOVA of the CDA mean amplitudes yielded a significant main effect of Distractor Type, $F(4, 80) = 5.535$, $p < .001$, $\eta_p^2 = 0.217$. Post-hoc tests with Holm correction revealed that the CDA amplitude to be significantly larger with the SF distractor than with the DCS and CM distractors as well as the TO baseline (mean differences > 0.495, ps < .04), and marginally larger compared to the DC distractor (mean difference = 0.528, p = .056), with comparable amplitudes among the latter four (TO, DC, DCS, and CM) conditions (ps > .369, BF < 0.094). This pattern suggests that only the intra-dimension distractor underwent additional processing in working memory (e.g., Chen et al., 2022; Eimer et al., 2004; Eimer & Driver, 2000; Forster et al., 2016; Töllner et al., 2009).

Distractor-elicited CCN (50–250 ms). The CCN originating from the central region (C3 and C4) reflects spatial-attentional modulations induced by lateral sensorimotor activity (Eimer et al., 2004; Eimer & Driver, 2000; Forster et al., 2016; Töllner et al., 2009). A one-way repeated-measures ANOVA of the CCN amplitude yielded a highly significant main effect of Distractor Type, $F(4, 80) = 45.285$, $p < .001$, $\eta_p^2 = 0.694$. As revealed by post-hoc comparisons, this component was attributable to the CM distractor: this condition differed significantly from all other conditions (ps < .001), without a difference among the latter (ps > .999). In other words, the CCN component was related exclusively to the processing of the lateralized vibro-tactile distractor signal.

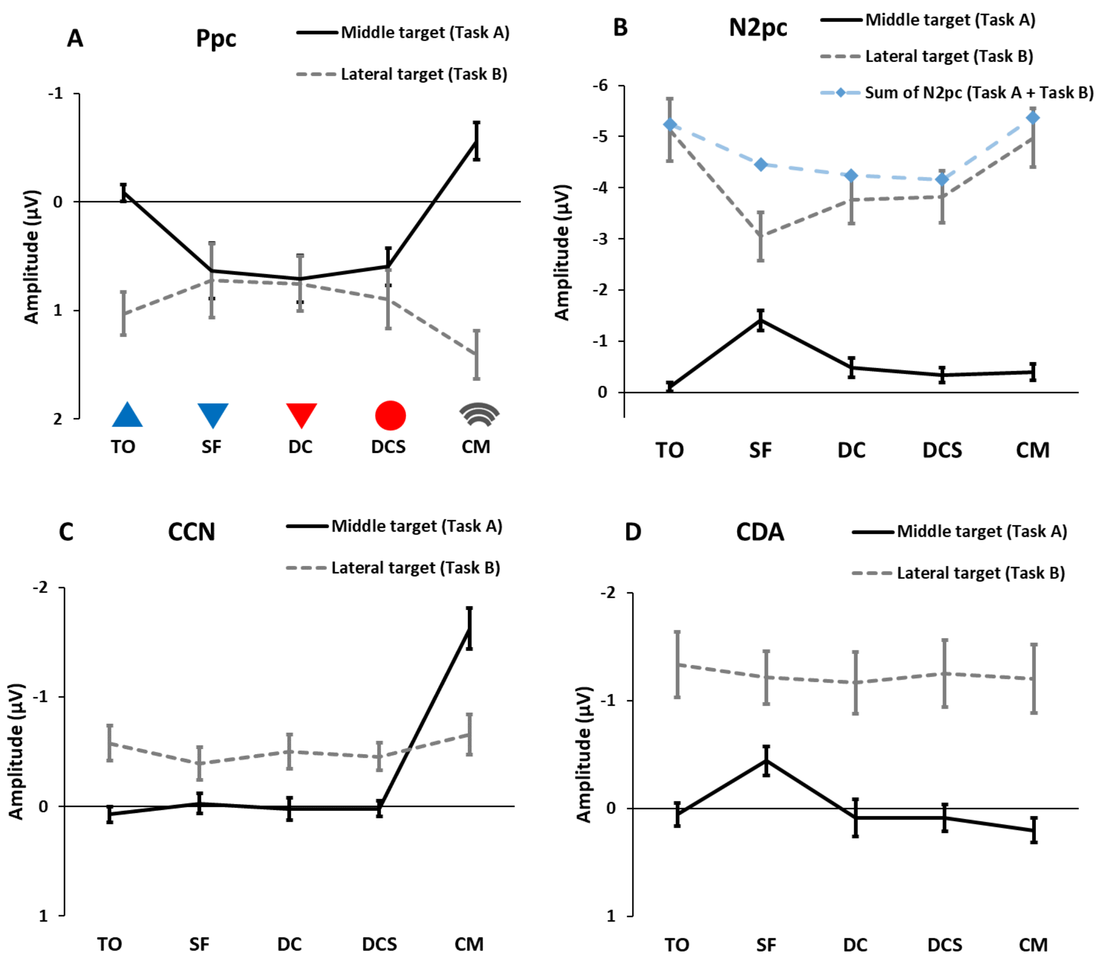

Figure 4. Mean amplitudes of the Event-Related Lateralization components – Ppc (A), N2pc (B), CCN (C), and CDA (D) – across the five Distractor-Type conditions: target-only (TO) and same-feature (SF), different-color (DC), different-color and different-shape (DCS), and cross-modal (CM) distractors. Solid lines depict the amplitudes for Task A (target located on the vertical midline), gray dashed lines those for Task B (target located laterally); the blue dashed line in figure B presents summed N2pc amplitudes from Tasks A and B. Error bars represent the standard error of the mean.

Task B (Vertical-midline distractor/lateral target): target-elicited lateralizations

The target-related ERL difference waveforms from PO7/PO8 are depicted in the upper-right panel of Figure 3. Visual inspection shows a pronounced negative N2pc amplitude around 200-300 ms in all conditions. The lower-right panel shows the ERL difference waveform from C3/C4. As there were no lateral distractors in Task B (in contrast to Task A), there was no significant CCN component. The statistical analyses for the various components of interest are reported in separate subsections below.

Ppc (90–140 ms). A one-way repeated-measures ANOVA of the Ppc amplitude revealed a significant main effect of Distractor Type, $F(4,80)=5.175$, $p < .001$, $\eta_p^2 =.206$ (as seen in Figure 4 A). The largest Ppc was elicited in the CM condition, significantly larger compared to the DC and DCS conditions (mean differences > 0.51, ps < .032), and marginally larger relative to the SF condition (mean difference = 0.684, $p = .051$). Importantly, the mean amplitudes of the Ppc were significantly positive for all conditions (ps < .024, one sample t-test for all conditions). The observation that Ppc amplitudes are significantly positive across all conditions, including lateral visual distractors in Task A and lateral targets in Task B, supports the notion that Ppc indicates early sensory processing.

N2pc (150–210 ms). The lateralized target elicited a strong N2pc in all conditions (simple t-tests to zero, ps < .001) – though with the N2pc amplitude fluctuating across the various distractor conditions, statistically evidenced by a significant Distractor-Type effect, $F(4,80) = 13.289$, $p < .001$, $\eta_p^2 = .399$ (see Figure 4 B): the N2pc amplitude was significantly larger without a distractor in the display (TO) compared to conditions with a visual distractor (SF, DC, and DCS conditions: mean differences > 1.311, ps < .01). In contrast, the target-related N2pc was not affected by the presence of a tactile distractor (CM vs. TO condition: mean difference = 0.160, $p = .628$, BF = 0.365; CM vs. SF, DC, DCS: mean differences > 1.150, ps < .025). Importantly, with visual distractors in the display, the N2pc amplitude was significantly reduced in the SF compared to both the DC (mean difference = 0.716, $p = .004$) and DCS (mean difference = 0.775, $p = .026$) conditions, without a significant difference between the latter (mean difference = 0.060, $p = .703$, BF = 0.243). While showing that the type of distractor has a considerable impact on the N2pc amplitude, it is worth noting that the N2pc amplitude displayed a gradual decrease across different types of distractors, with the largest amplitude observed for the CM condition, followed by the DCS and DC conditions, and the smallest amplitude for the SF condition. This pattern of results is in line with the behavioral findings, which showed the reverse pattern.

Spatial Template Effects on Attention Allocation (N2pc from Task A and Task B)

Assuming the N2pc amplitude provides an indicator of the distribution of attentional resources (cf. Gaspar & McDonald, 2014; Liesefeld et al., 2017), we calculated the additive – distractor-elicited N2pc plus target-elicited N2pc – difference waves (see the blue line in Figure 4B) and compared them to the target-only (TO) condition. Although a one-way repeated-measures ANOVA yielded a significant main effect, $F(4, 80) = 4.925$, $p = .015$, $\eta_p^2 =$

0.198, subsequent post-hoc tests revealed that none of the conditions with distractors (SF, DC, DCS, CM) significantly deviated from the TO condition (ps = .657, .262, .081, and .999, respectively). This pattern is consistent with the idea that, on distractor-present trials, attention was shared between the target and the distractor item, with the total amount of attention being a fixed (limited) resource.

We are testing the effect of the spatial template and aim to understand the impact of the distractor location on attentional resource allocation by comparing the N2pc amplitudes in conditions with Same-Feature (SF) distractors against the baseline of half the target-only (TO) N2pc amplitude. This baseline represents an estimated 50% allocation of attentional resources to the target and the other 50% allocation to the Same-Feature distractor.

For the "Distractor Location Shielding" hypothesis, we anticipated a significant reduction in N2pc amplitude for Task A's SF condition. Our results substantiated this hypothesis, showing that the N2pc amplitude elicited by lateral SF distractors was significantly lower than the half amplitude from the target-only condition, $t(20) = -4.537$, $p < .001$. In contrast, there was no significant "Target Location Enhancement," as the SF condition's target-elicited N2pc amplitude in Task B was not significantly larger than half the target-only condition's amplitude, $t(20) = 1.144$, $p = .266$. These results show the spatial template works in the shielding distractor location rather than enhancing the target location.

CDA (mean amplitude: 280–400 ms). The CDA amplitudes (Figure 4D) were < -1.166 µV, all significantly smaller than 0 (simple t-tests, all ps < .001) with comparable across all Distractor-Type conditions, $F(4, 80) = 0.254$, $p = .846$, $\eta_p^2 = .013$. This suggests that the presence of any type of distractors does not influence the post-attentional processing of the (lateral) target in working memory.

CCN (50–250 ms). The CCN amplitudes were smaller than -0.395 µV, and significantly different from the zero across all conditions (ps < .008) . This observation can be attributed to the spread of N2pc voltages from the occipito-parietal area (PO7/PO8) to the sensorimotor area (C3/C4). The pronounced N2pc amplitude, exceeding -5 µV, may overshadow the relatively smaller CCN voltages (around -0.5 µV). Recall that in Task B, the tactile distractor stimuli were left-right symmetrical (stimulating the thumbs of the left and right hand), so one would not expect the tactile distractor to induce a stronger lateralization than visual distractors (on the vertical midline). Consistent with this, the CCN amplitudes were comparable across all conditions, $F(4,80) = 0.976$, $p = 0.425$, $\eta_p^2 = 0.047$.

ERPs related to conflict processing

Figure 5 displays the ERP waveforms obtained from Fz, Cz, and Pz. Visual inspection indicates a significant negative-going N1 between 40–130 ms evoked by vibrotactile distractors in the cross-modal distractor condition. There were strong differences around N2 and P3 components (particularly for channel Pz), indicative of the occurrence of conflict and inhibition processes (Donkers & van Boxtel, 2004; Folstein & Van Petten, 2008; Kałamała et al., 2018; Kopp et al., 1996; Larson et al., 2014; Tops & Wijers, 2012; Verleger, 2020; Yeung et al., 2004). Next, we report each component individually.

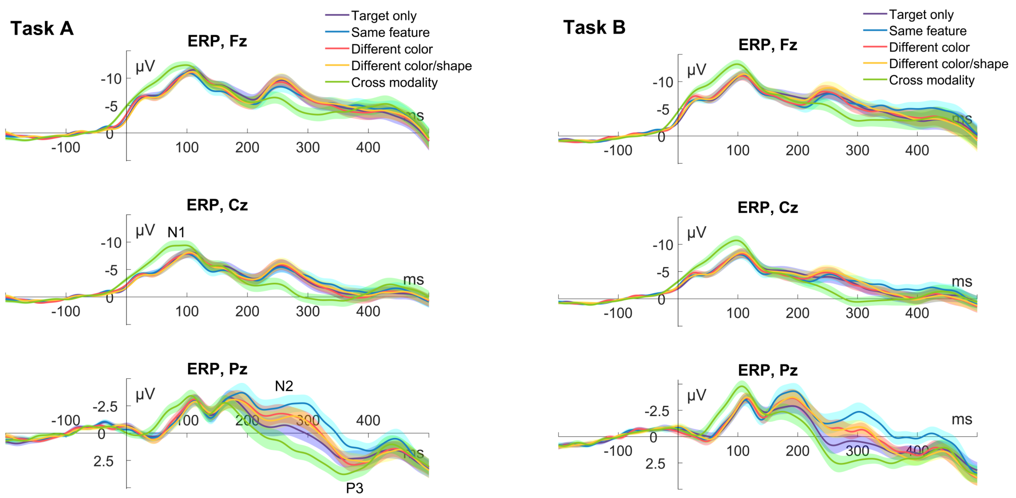

Figure 5. ERPs recorded from midline channels Fz, Cz, and Pz in both Task A (vertical midline target, left panel) and Task B (lateral target, right panel) for the five Disractor-Type conditions: (i) target-only condition (TO); (ii) same-feature (SF) distractor; (iii) different-color (DC) distractor; (iv) different-color and different-shape (DCS) distractor; and (v) cross-modal (CM) distractor. Error bars represent the standard error of the mean.

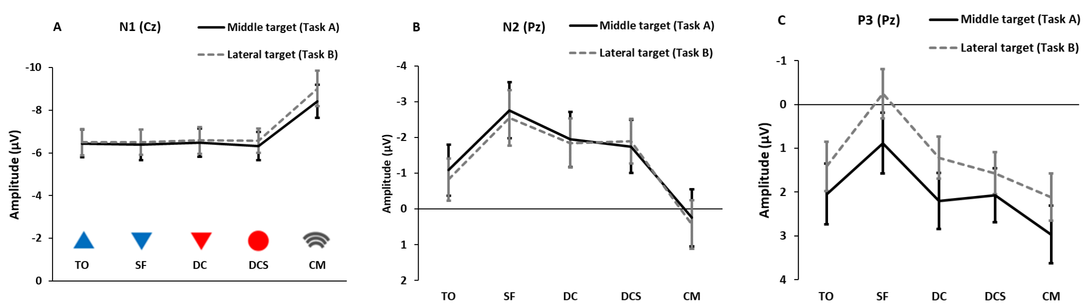

Figure 6. ERP mean amplitudes for the N1 sourced from channel Cz (A), and the N2 (B) along with the P3 (C) from channel Pz, across the various Distractor-Type conditions: (i)

target-only condition (TO); (ii) same-feature (SF) distractor; (iii) different-color (DC) distractor; (iv) different-color and different-shape (DCS) distractor; and (v) cross-modal (CM) distractor. Solid lines depict the data from Task A (target at vertical-midline position), the gray dashed lines the data from Task B (target located laterally). Error bars represent the standard error of the mean.

N1 (Cz, 50–150). In both Tasks A and B, the N1 mean amplitude was larger in the tactile (CM) distractor condition vs. the other conditions (main effect of Distractor Type, $F(4,80) = 31.649$, $p < .001$, $\eta_p^2 = 0.613$), with comparable amplitudes between the two tasks (main effect of Task, $F(1,20) = 0.308$, $p = .59$, $\eta_p^2 = 0.015$; Task and Distractor-Type interaction, $F(4,80) = 1.085$, $p = .370$, $\eta_p^2 = 0.051$). Post-hoc comparisons confirmed the amplitude in the CM condition to be significantly larger compared to all other conditions (ps < .001), without any differences among the latter (TO, SF, DC, DCS; ps > .9). Thus, the tactile distractor elicited a larger central N1 component compared to the other conditions.

N2 (Fz, 230–310 ms). Analysis of N2 amplitude in frontal area indicated a significant effect of distractor type (Distractor-Type effect, $F(4,80) = 27.606$, $p < .001$, $\eta_p^2 = .304$), with the tactile distractor condition (CM) showing significantly higher N2 amplitudes than all other conditions (ps < .001). No other significant differences emerged between the remaining distractor types, implying a similar level of conflict processing for these visual features. Interestingly, subsequent analysis reveals that the amplitude of N2 at Fz also varies with response speed, particularly when comparing fast and slow responses. (Please see the subsequent section.)

N2 (Pz, 230–310 ms). The N2 component at Pz demonstrated a significant variation across distractor conditions (Distractor-Type effect, $F(4,80) = 46.032$, $p < .001$, $\eta_p^2 = .446$), indicating a differential processing of the distractors based on their feature similarity to the target. The condition with the same-feature (SF) distractor elicited the largest N2 amplitude across all conditions (all ps < .05), signaling the strongest conflict where the distractor matched the target features. The differences between the different-color (DC) and different-color and different-shape (DCS) distractors were not significant ($p = .698$), yet both elicited larger N2 amplitudes than the target-only (TO) condition (ps < .01). Notably, the tactile distractor (CM) condition resulted in the smallest N2 amplitude, markedly smaller than the visual-distractor conditions (SF, DC, DCS) and the no-distractor (TO) condition (ps < .001). This pattern is similar to the results of N2pc, suggesting that the N2 component is associated with attentional allocation.

P3 (Pz, 330-430 ms). The P3 component at Pz, too, was significantly modulated by Distractor Type, $F(4,76) = 29.996$, $p < .001$, $\eta_p^2 = .6$. There was also an effect of Task ($F(1,20) = 9.206$, $p = .007$, $\eta_p^2 = .315$), but no interaction ($F(4,80) = 0.868$, $p = .462$, $\eta_p^2 = .042$). Post-hoc comparisons revealed the same-feature distractor (SF) condition to elicit the smallest P3 amplitude, compared to all other conditions (ps< .004). There were no significant differences among the target-only (TO), different-color distractor (DC), and different-color different-shape distractor (DSC) conditions (ps> .9). The tactile distractor (CM) induced the largest P3 compared to the other four conditions (ps<.004). This pattern suggests that only the same-feature distractor induced a strong conflict, where the small P3 amplitude may be related to conflict resolution and successful distractor inhibition (Donkers & van Boxtel, 2004; Folstein & Van Petten, 2008; Kałamała et al., 2018; Kopp et al., 1996; Larson et al., 2014; Tops & Wijers, 2012; Verleger, 2020; Yeung et al., 2004).

Discussion

This study aimed to explore how spatial attentional selection and similarity-based attentional shielding between distractors and targets interact, drawing on EEG-derived attentional signatures. With a fixed target and predefined location within our tasks, participants could employ a 'target-template'-based search strategy (Geng, 2014; Theeuwes et al., 2022; van Moorselaar & Slagter, 2020), alongside space-based attentional tuning (e.g., O'Grady & Müller, 2000). The objective was to assess whether spatial templates serve to shield distractor locations or to enhance target location processing. Our findings indicate that spatial attentional templates primarily provide a shielding effect at distractor locations, rather than enhancing target location processing at the target location, as evidenced by ERL results.

The experimental design included lateralizing either target or distractor in two distinct tasks, allowing for a detailed analysis of ERL components like Ppc, CCN, N2pc, and CDA. The results showed that all lateralized stimuli (whether targets or distractors) were registered by the sensory system around 100 ms post-stimulus, as evidenced by the Ppc component. This effectively ruled out Ppc as a function of early distractor suppression. Instead, only distractors sharing features with the target triggered a subsequent N2pc, indicating attentional engagement and minimizing attentional capture by non-target features or modalities, consistent with dimension-/modality-weighting accounts (Liesefeld et al., 2022; Liesefeld & Müller, 2019; Müller et al., 1995; Zhang et al., 2019). Our study also identified conflict effects[15], referring to the interference arising from the opposite orientation of the target and distractor (both represented triangles with one facing upward and the other facing downward). Effectively engagement with intra-dimension distractors (i.e., SF and DC) was marked by increased amplitudes of N2 and P3, which are indicative of conflict processing (Donkers & van Boxtel, 2004; Folstein & Van Petten, 2008; Kałamała et al., 2018; Kopp et al., 1996; Larson et al., 2014; Tops & Wijers, 2012; Verleger, 2020; Yeung et al., 2004).

Theoretically, if attention was equally distributed to the target and the Same-Feature distractor (note: the SF distractor is the same as the target, but with 180-degree rotation), the N2pc amplitude would be exactly 50% of the (lateral) target-only condition. Our results corroborated the hypothesis that the spatial template worked as "Distractor Location Shielding," where the N2pc amplitude for the SF condition in Task A was significantly lower than the theoretical half of the target-only N2pc amplitude. And we did not see the "Target Location Enhancement" effect. Additionally, the outcomes align with the "Down-Weighting of Non-target Feature/Dimension/Modality" hypothesis, where participants engaged less with distractors lacking target features, evidenced by the diminished or absent N2pc amplitudes and the absence of the P_D component. The current task showed the down-modulation of distractions by reducing attentional engagement or ignoring rather than active suppression.

Effects of Spatial Template represented by N2pc

Drawing from our prior research (Tsai et al., 2023), we posited that attentional resources allocated to the target and distractor were fixed, a finding corroborated by the current N2pc summation results (Figure 5B, the blue dashed line), following analytical methodologies similar to Gaspar & McDonald (2014) and Liesefeld et al. (2017). The current study further investigated how attention is allocated between the targets and distractors across different dimensions and modalities. Previously (Tsai et al., 2023), we assessed how attention might be shared between a target and its corresponding distractor by measuring the N2pc component—an index of where attention is engaged. We looked at cases where participants focused on the target alone (target-only, TO), the distractor alone (distractor-only, DO), and when they had to deal with both a target and a distractor (target-distractor, TD). By comparing these conditions, we revealed The sum of TD and DO N2pc amplitudes aligns

[15] In our study, we intentionally implemented incongruent response-critical features in the intra-dimension condition to investigate attentional capture. Distractors with response-critical incongruent feature slow down reaction times (Eriksen & Eriksen, 1974), which could provide clear evidence of attentional capture by the distractor. We excluded the condition with a response-critical congruent setup, because the congruent condition might lead to faster responses, which may become ambiguous whether the faster response is due to no engagement with the distractor or merely expedited processing.

equally with TO N2pc amplitudes, suggesting an even split of attentional resources (refer to Appendix Figure S4 in Tsai et al., 2023 for details).

However, the simultaneous lateralization of both target and distractor, as noted in Tsai et al. (2023), posed potential challenges because both could contribute to the lateralizations. Here, we refined this approach by assigning the target or distractor to a fixed midline position, thereby ensuring that lateralization effects are triggered solely by the stimulus positioned laterally. Assuming that attentional resources are constant, the N2pc amplitude in the Target-Only condition (baseline of total 100% attentional resources) from Task B (where the target was lateral) represented the full attentional capacity. When we included a distractor with features identical to the target (which we call a Same-Feature or SF distractor), we initially assumed that attention would be split equally between the target (50% of attentional resources) and the distractor (50%). However, our task design had the target and distractor in set positions that did not overlap, and participants knew where to expect each one. This knowledge allowed them to use their understanding of the space—the 'spatial template'—to manage their attention. So instead of dividing their attention in half between target and distractor, participants could adjust their focus, possibly reducing attention on the expected distractor's location (this is what we refer to as 'shielding') and keeping or even increasing their focus on the target location (referred to as 'enhancement'). The summation of N2pc provides insight into the spatial template's mechanism—whether it predominantly shields the distractor location, enhances the target location, or operates via a combination of both strategies.

Our ERL results offer evidence for the 'Distractor Location Shielding' effect within the spatial attentional framework. When participants encountered Same-Feature (SF) distractors, the N2pc amplitudes suggested that attention was strategically diverted away from the distractor locations. This behavior aligns with the expectation of the spatial template, which posits that individuals can anticipate and minimize attentional resources to known distractor locations, effectively reducing their potential interference. Interestingly, this shielding effect occurred without concomitant 'Target Location Enhancement.' The lack of increased target-elicited N2pc amplitudes in the presence of middle SF distractors compared to the half N2pc amplitude in the TO condition indicates that participants did not allocate extra attentional resources to the target location (lateral sides). This finding refines our understanding of the spatial template's role: it is employed primarily to prevent attentional capture by expected distractors, rather than to boost focus on the target.

Effects of Feature Template on Attentional Allocation

Our investigation into feature-based attentional templates was guided by three specific hypotheses to understand how attention is modulated based on feature similarity between targets and distractors. Firstly, the 'Distractor Down-Weighting' hypothesis suggested that attentional resources would be diminished for distractors not sharing target features, as indicated by reduced N2pc amplitudes and the absence of the P_D component, suggesting a lack of proactive or reactive suppression. Our results observed this where distractors not matching the target features elicited weaker attentional engagement.

We found that the same feature distractor caused the greatest interference, which was represented by the largest distractor-elicited N2pc. This is because the target shape and color would have the highest weights in the computation of the priority map and induce the attentional capture and allocation. The distractor with a partial target feature (e.g., DC) also showed minor effects. However, there are no significant effects from the cross-dimension and cross-modality distractors (i.e., DCS and CM conditions). This also aligns with the dimension-weighting/modality weighting account (Found & Müller, 1996; Liesefeld & Müller, 2019; Töllner et al., 2010). The dimensions and modalities unrelated to the target would be down-weighted, and no (little) resources would be deployed to these distractors.

Secondly, we explored the 'Proactive Suppression' hypothesis, which posited that participants could actively suppress distractors, known in advance by their locations, resulting in the absence of the N2pc and the presence of a P_D component. Our findings did not support this hypothesis, as we did not observe significant P_D components, indicating that proactive suppression might not be the primary mechanism in play. Previous studies usually observed P_D when the lateral salient distractor was presented (e.g., Gaspar and McDonald, 2014; Gapelin and Luck, 2018; van Moorselaar and Slagter, 2019). Furthermore, if participants learned the high-distractor-probability location, the P_D elicited by the distractor would be more obvious (e.g., Wang, et al., 2019). In our current study, the distractor location is known in advance and never overlapping with the target locations. However, in many studies, by manipulating distractor location probabilities, the target could still appear at the high-distractor-probability location. So, participants could not apply the very strict spatial template used in our current study. It seems the strict spatial template works in a manner like "ignoring" rather than "actively suppressing." The effect of ignoring is represented by the absence of both P_D and N2pc; in other words, the lateral stimulus did not cause significant lateralization, especially supported by the DCS condition.

The third hypothesis, 'Reactive Suppression' suggested that the system might enhance attention to target-related features, leading to engagement with distractors sharing these features, as indexed by N2pc. Many studies (e.g., van Moorselaar and Slagter, 2019; Liesefeld et al., 2017; McDonald et al., 2013) observed that participants deployed attention to the lateral distractor, then disengaged from the distractor. Therefore, the distractor-elicited N2pc came first, followed by P_D, which was the reactive distractor suppression. This case highlights that an inappropriate engagement—when the distractor is not the target—would result in reactive suppression, signaled by a subsequent P_D component. Our data did not exhibit this pattern, pointing towards a different interaction between feature-based attention and distractor suppression. Although the lateral Same-Feature distractor (SF) successfully induced significant N2pc, modulated by the spatial template, the amplitude is less than half the amplitude of the Target-Only elicited N2pc. This means that the amount of attentional engagement to the lateral SF distractor is not so influential, and initiating the suppression mechanism seems unnecessary.

The absence of the P_D component in our results is particularly telling. It indicates that while the feature-based template may mainly modulate attentional engagement (as reflected by the N2pc), it does not necessarily lead to active suppression (no significant P_D), even when distractors share features with the target. Although many studies took P_D as the index of distractor suppression, the exact function is still controversial (see the review from Gaspalin et al., 2023), especially the alternative accounts are merging, like Kerzel and Huynh Cong (2020), suggesting P_D reflects the selection of nontarget locations. The P_D seems like a "re-orienting" manner, with participants redirecting attention to the distractor's opposite side or shifting away from the distractor. Even though the P_D may be for redirecting or shifting away from the distractor rather than suppression, our current study did not need to involve this re-orienting process because the target was never on the opposite side of the distractor. Collectively, these findings illuminate the nuanced role of feature-based templates in attentional allocation and engagement. They highlight the attentional system adept at adjusting its focus based on feature relevance, engaging with stimuli that share features with the target but not necessarily resorting to active suppression.

Registered but not Engaged in Cross-Dimension and Cross-Modality Distractors

In both Task A (lateral distractor) and Task B (lateral target), the significant Ppc component was still observed, suggesting that the lateral stimulus (both lateral distractor or target) was registered in the sensory system at an early stage without further deep processing. We did not find any significant late P_D components in the present study. The question then becomes whether we should interpret this early positivity as an early registration of general sensory processing Ppc, or as early suppression P_D. We consider this early positive component as Ppc just for sensory registration, because in Task B, the lateral target elicited a similar significant Ppc, whereas no suppression was required for this lateral target. Therefore, it is more reasonable to attribute this positive component to the early sensory processing of the lateral stimuli rather than early suppression. This interpretation aligns with previous studies (Dodwell et al., 2021; Tsai et al., 2023; Zinchenko et al., 2020).

The significant CCN from C3/C4 that we observed in the tactile distractor condition (CM) is consistent with the notion that the CCN is an indicator of registration of tactile sensation from salient tactile stimuli (Eimer et al., 2004; Eimer & Driver, 2000; Forster et al., 2016; Nasemann et al., 2023; Töllner et al., 2009; Tsai et al., 2023). In Task A, where the target was always in the middle, the lateral high-frequency vibration distractor in the cross-modality distractor condition was registered by the sensory system and represented by CCN, but it did not impair behavioral performance. This suggests that the tactile modality was down-weighted in favor of the visual target search, in line with the modality weighting account (Nasemann et al., 2023; Töllner et al., 2009).

For Task A, the distractor-elicited N2pc component (from PO7/PO8) did not show a significant difference between the Cross-modality (CM) and the Target-Only baseline (TO) conditions since there were no lateral visual stimuli in the former. In Task B, where the target was always lateral, the middle tactile distractor did not reduce the target-elicited N2pc amplitude, indicating that the task-irrelevant tactile distractor did not interfere with deploying most attentional resources to the lateral target. The results of both tasks suggested that participants registered the task-irrelevant distractor but ignored it without engagement.

Our findings of no behavioral interference from the cross-modality vibro-tactile distractors are consistent with a recent report by Mandal and Liesefeld (2022) that showed spatially localized auditory distractors failed to interfere with the visual search for a shape-defined target. Even though auditory and somatosensory stimuli are fundamentally different in terms of space coding, the MWA suggests that distractors defined in irrelevant modalities can generally be kept out of attentional-priority computations. This allows the search-guidance system to effectively down-weight any feature-contrast signals generated by distractors in a non-target-defining modality, consistent with the behavioral data.

Conclusion

In conclusion, our study elucidates mechanisms of spatial and feature-based attentional templates within the variant Eriksen Flanker Task, revealing that spatial templates primarily shield distractor locations to reduce attentional engagement without necessarily enhancing target focus. By examining event-related lateralizations, we demonstrated that attentional resources are finely modulated based on feature similarities, which supports the 'distractor down-weighting' hypothesis. Our findings suggest a limited and strategic allocation of attentional resources, with minimal engagement from target-irrelevant distractors. We did not observe the P_D component when the distractor location was known to participants. The current study suggests that if participants can apply shielding and down-weighting approaches for distractor handling to avoid distraction, it would not be necessary to involve proactive or reactive suppression mechanisms commonly reflected by the P_D component.

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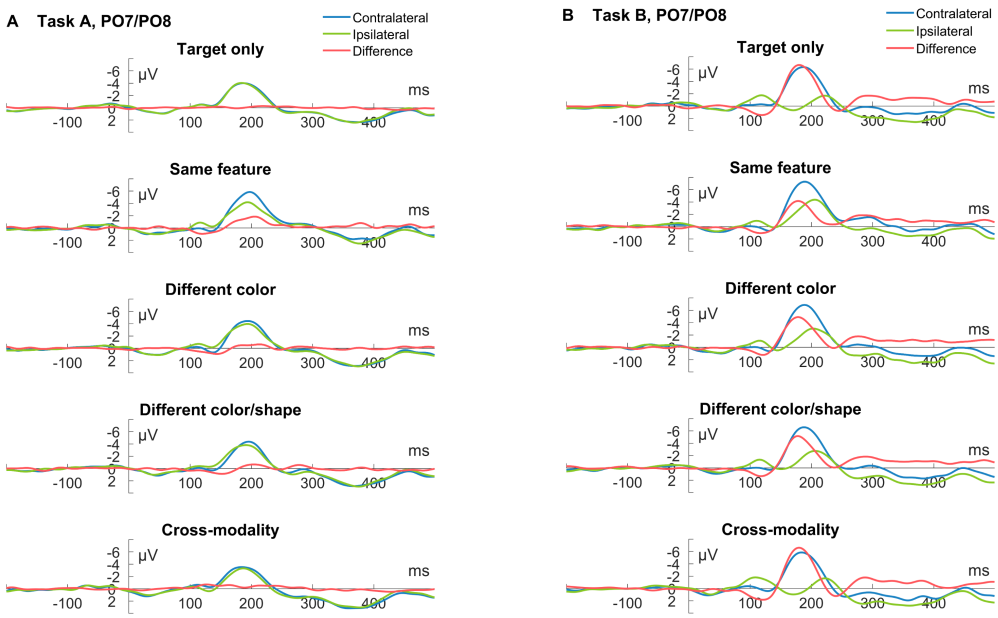
Appendix

ERP waves and their correspondent difference waves

Our ERP analyses focused on event-related lateralizations (ERLs), that is, the difference waves between the contralateral and ipsilateral responses to lateral distractors in Task A and, respectively, lateral targets in Task B (as shown in Figure A1) for the various components of interest.



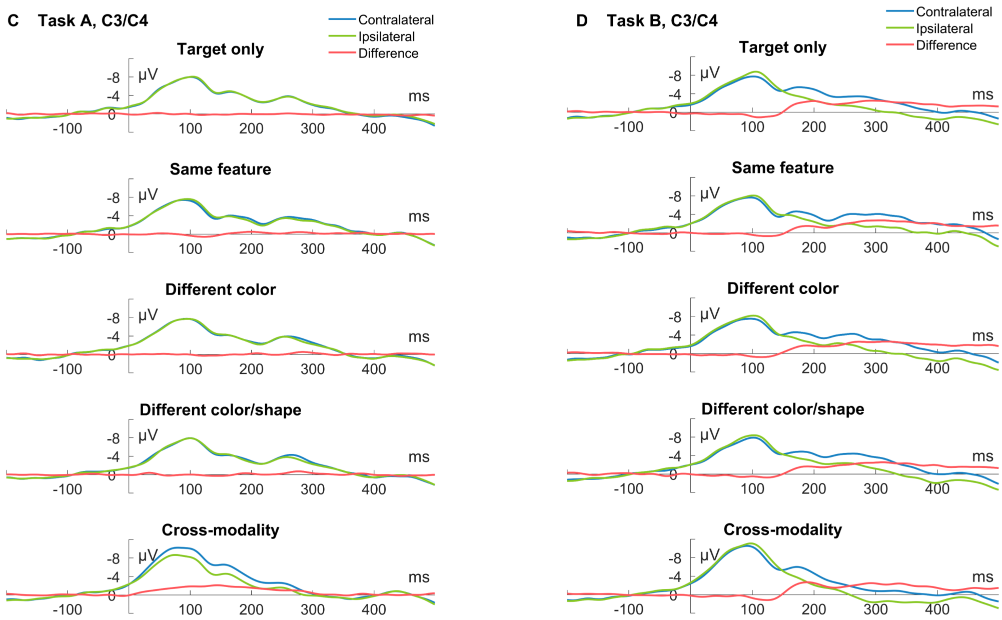
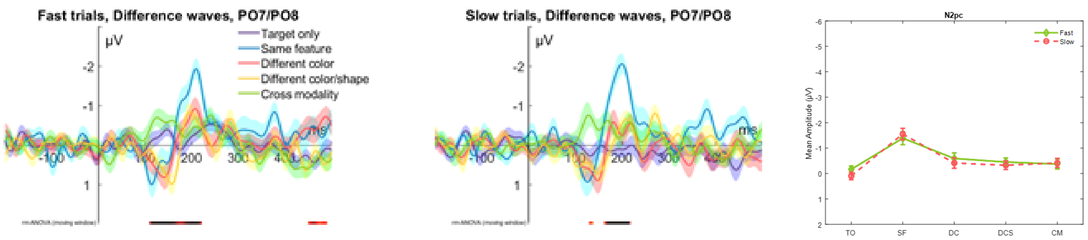


Figure A1. Event-Related Potential (ERP) and Lateralization (ERL) waveforms for channels PO7/PO8 (A and B) and C3/C4 (C and D). The ERPs were collected from contralateral (blue lines) and ipsilateral (green lines) locations relative to the lateral distractor location in Task A (Panels A and C) and, respectively, the lateral target location in Task B (Panels B and D), for the five Distractor-Type conditions (including the target-only condition). The red lines depict the ERLs, i.e., the difference waveforms computed by subtracting the ipsilateral the contralateral ERPs. Panels A and B present the data recorded from PO7 and PO8, revealing lateralizations in the parietal-occipital area. Panels C and D present the data recorded from C3 and C4, illustrating the lateralization in the sensorimotor area.

The comparison of fast- and slow- trials

In this study, we aim to elucidate the mechanism behind the flanker effects. So, manipulating the location of the target and distractor was critical for examining the ERLs. In the traditional flanker task, we do not know whether participants engaged attention with the flankers. Given that the display in the classical paradigm was symmetric (e.g., < < > < <), it was hard to observe the ERLs (i.e., no lateralization, especially no Ppc and no N2pc). The slower response in the incongruent trials would be attentional deployment to the flankers. However, participants should have a spatial template to filter out the lateral stimuli next to the middle target (in Task A, and vice versa in Task B). We do not know whether the attentional engagement to the lateral flanker caused the slow response or just the conflicts between target-distractor orientations. The following sections of the fast vs. slow response trials analysis would give us more information about the potential factors. Ideally, if the spatial and feature templates functioned effectively, the reaction time would be the fastest. In contrast, if either the spatial or feature template failed, the response speed would be longer, and the ERL indexes could answer whether the delay was caused by the attentional capture by the distractors or the reduced efficiency of resolving conflicts.

A: Task A



B: Task B

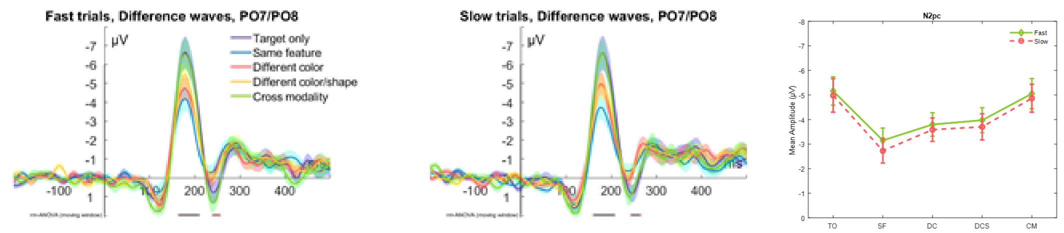
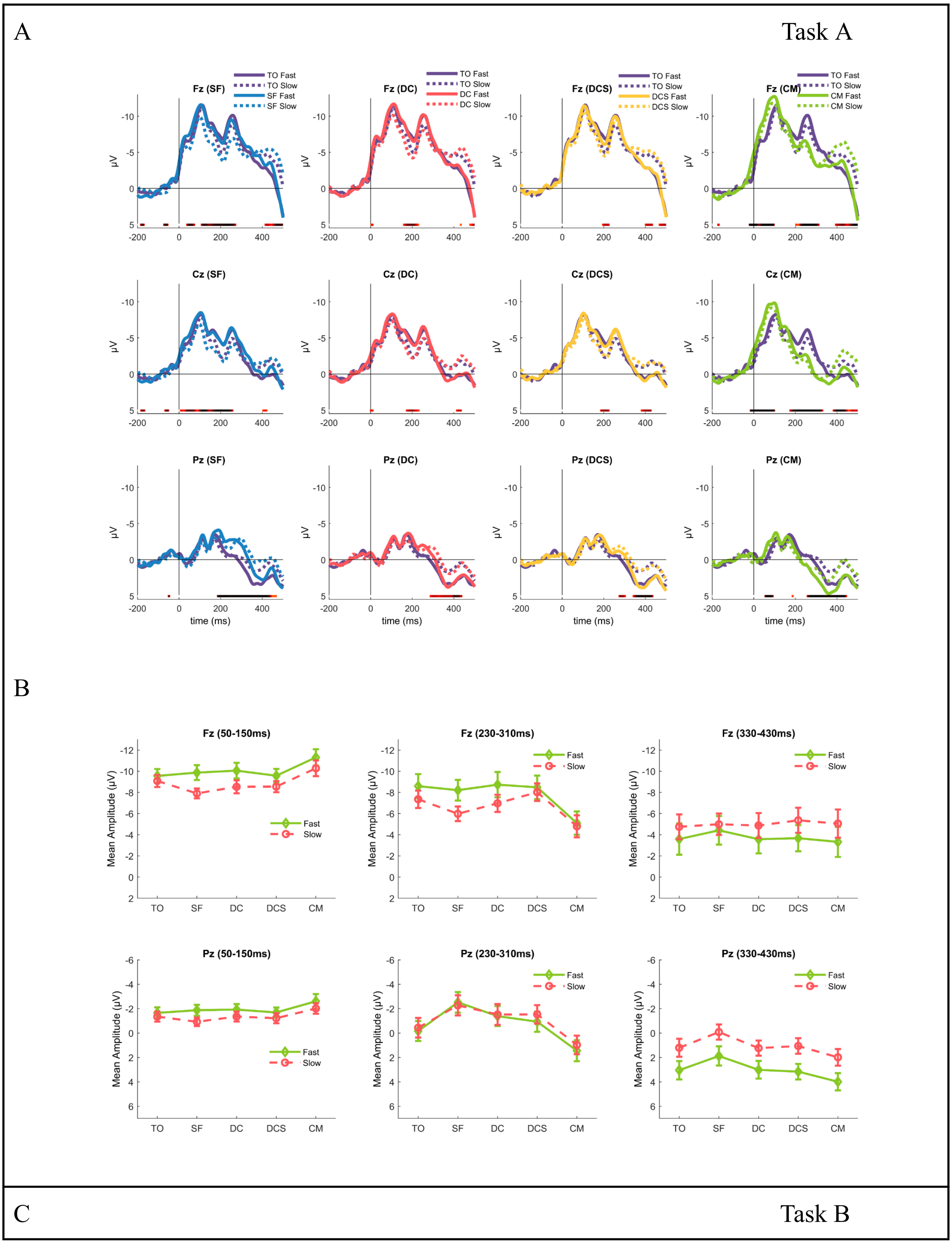


Figure A2: The Event-Related Lateralizations (ERLs) for both fast and slow response trials, especially highlighting the N2pc component. In Task A, it's evident that the N2pc amplitude remains consistent across both types of trials when the SF distractor is introduced, implying that the reaction time isn't significantly influenced by attentional engagement with the lateral SF distractor. However, in Task B, there's a clear difference in the target-elicited N2pc amplitude between fast and slow trials, with the former having a greater amplitude. This suggests that a higher attentional engagement with the lateral target expedites the response across all distractor types. Overall, the figure elucidates the pivotal role of attentional engagement with the lateral target in determining response speed, while engagement with lateral distractors remains less influential in this aspect.


A
Task A
Fz (SF)
TO Fast
TO Slow
SF Fast
SF Slow
Fz (DC)
DC Fast
DC Slow
Fz (DCS)
DCS Fast
DCS Slow
Fz (CM)
CM Fast
CM Slow
Cz (SF)
Cz (DC)
Cz (DCS)
Cz (CM)
Pz (SF)
Pz (DC)
Pz (DCS)
Pz (CM)
μV
time (ms)
B
Fz (50-150ms)
Fz (230-310ms)
Fz (330-430ms)
Pz (50-150ms)
Pz (230-310ms)
Pz (330-430ms)
Mean Amplitude (μV)
Fast
Slow
TO
SF
DC
DCS
CM
C
Task B

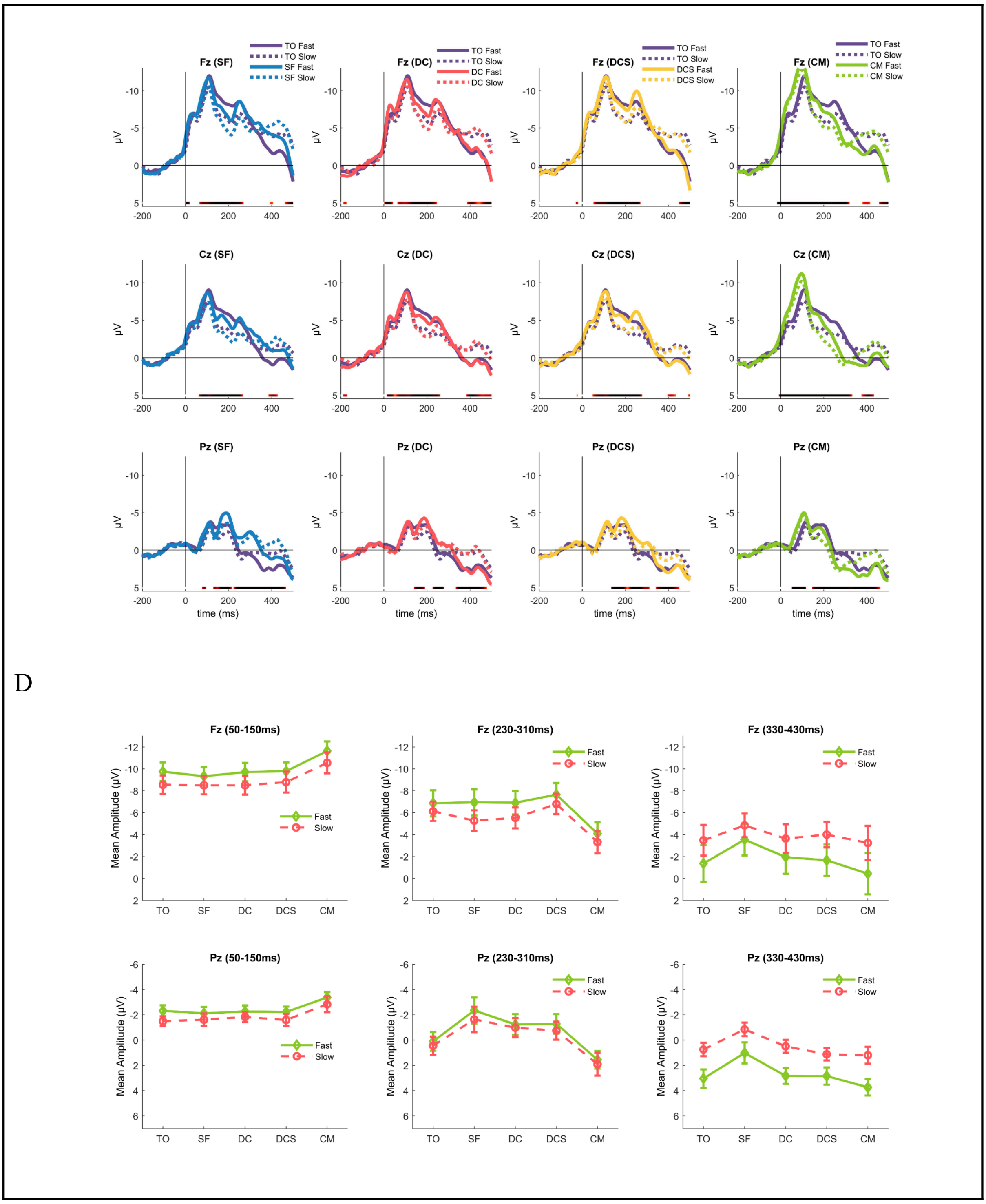


Figure A3: ERPs and Conflict Resolution

A (Task A) and **C** (Task B): ERPs from various trials, on the Fz, Cz, and Pz. Solid lines = fast-response trials; Dotted lines = slow-response trials. **B** (Task A) and **D** (Task B): The mean amplitude for N1 (40–130 ms), N2, (170-310 ms) and P3 (330-430 ms) from Fz and Pz. Here, we emphasize the interaction of the N2 component from Fz: Reduced amplitude in SF and DC during slow-responses suggests compromised attentional control. Fast-responses maintain consistent N2 amplitude across conditions, implying efficient attentional processes.

Attentional Engagement (ERL: N2pc)

In Task A, focused on the same-feature (SF) condition, we observed that the distractor-elicited N2pc amplitudes were remarkably consistent between fast and slow response trials. This consistency indicates that the degree of attentional engagement towards distractors remains stable regardless of the speed of response (detailed ANOVA results are presented in Table 1 and Figure 8). This finding challenges the expectation that faster responses might be associated with diminished attentional engagement with distractors.

In contrast, the scenario for Task B brought to light a different aspect of attentional engagement. Here, in fast-response trials, we noticed a pronounced enhancement in target-elicited N2pc, aligning with the hypothesis that increased attentional engagement is a contributing factor to swifter responses. This enhancement suggests that when participants respond quickly, their attentional resources are more efficiently and more intensely focused on the target, as reflected by the amplified N2pc amplitudes. While attentional engagement with distractors appears to be unaffected by response speed, the focus on targets intensifies during faster responses. This pattern underscores the nuanced role of N2pc in reflecting distinct facets of attentional engagement, depending on the nature of the stimuli (distractor vs. target) and the immediacy of the cognitive response.

Early Sensory Processing (ERPs: N1)

Fast-response trials were marked by a significant increase in N1 amplitude at both electrode Fz and Pz, signaling facilitation of early sensory processing that may expedite response execution. Notably, visual distractors did not differentially influence N1 amplitudes across conditions, apart from the distinct response to the high-frequency tactile (cross-modal, CM) condition (refer to Table 2).

Attentional Control (ERP: frontal N2)

The role of the frontal N2 amplitude in cognitive processing is a complex issue in attention research. In our study, the N2 amplitude intriguingly diminished during slow-response trials when the same-feature (SF) distractor was present, an observation that seems to diverge from traditional conflict theory. This attenuation hints at potential lapses in attentional control, a finding detailed in Table 2. Notably, this reduction in amplitude conflicts with the commonly held view that incongruence amplifies the N2 amplitude, typically interpreted as heightened conflict detection.

Our results compel a reevaluation of the N2's functional attribution. The fact that N2 amplitude reduction was exclusive to slow-response trials in the presence of an SF distractor suggests that, within our modified paradigm, the N2 may not serve as a straightforward index of conflict. Instead, it appears to reflect a more nuanced aspect of attentional control, possibly related to the efficiency in handling stimulus conflict. This perspective is reinforced by the stability of N2 amplitudes across fast-response trials, regardless of distractor type. Such uniformity across distractor types implies that rapid responses are mediated by robust attentional control mechanisms that effectively navigate the cognitive challenges posed by conflicting stimuli.

Attentional Allocation (ERP: parietal N2)

Our analysis revealed a noteworthy correspondence between the parietal N2 and the N2pc components, particularly in the context of attentional resource allocation. Specifically, in the same-feature (SF) condition, the parietal N2 demonstrated heightened attentional resource engagement compared to the different-color (DC) and different-color and shape (DCS) conditions. This pattern mirrors the N2pc findings, suggesting a coherent neural response across these measures in processing attentional demands. Interestingly, the tasks involving only the target (TO) and cross-modal (CM) conditions evoked minimal resource allocation, as indicated by lower parietal N2 amplitudes. This observation aligns with the understanding that these conditions pose less of a cognitive challenge, thereby requiring fewer attentional resources.

A crucial aspect of our findings is the apparent immunity of parietal N2 amplitudes to variations in response speed. Unlike the frontal N2, where only the SF condition exhibited sensitivity to response times, the parietal N2 maintained consistent amplitudes across fast and slow responses. This consistency in the parietal N2, regardless of response speed, contrasts with the frontal N2's selective sensitivity and highlights a potentially different role of the parietal N2 in cognitive processing. The stability of the parietal N2, irrespective of response speed, starkly contrasts the N1 and P3 components, which showed significant differences between fast and slow responses. While the N1 and P3 amplitudes varied with response speed, indicating their sensitivity to the rapidity of cognitive processing, the parietal N2's steadfastness suggests a more stable role in attentional allocation that is not directly influenced by the speed of response.

Working Memory Updating (ERP: parietal P3)

The P3 component, particularly its parietal manifestation, has been implicated in a wide array of cognitive functions, ranging from working memory updating to the allocation of attention and the processing of stimulus significance. Our findings contribute to this discourse by demonstrating that faster responses are concomitant with larger P3 amplitudes at electrode Pz (refer to Table 2). This relationship underscores the role of P3 in facilitating efficient working memory processes, as more prompt reactions are coupled with more pronounced P3 responses.

Contrastingly, the appearance of the same-feature (SF) distractor resulted in a significant reduction of P3 amplitude (but no interaction with response speed), suggesting a disruption in these cognitive processes. This dampening effect may implicate the P3 in the brain's evaluation of stimulus relevance, supporting the notion that P3 amplitude reflects the updating of working memory in response to task-relevant stimuli. Such interpretation aligns with previous research indicating that P3 amplitude is sensitive to the allocation of attentional resources and the processing of salient information (Polich, 2007; Donchin & Coles, 1988).

However, the attenuated P3 response in the presence of the SF distractor also presents a challenge to the broader understanding of the P3's role in error detection or response inhibition, as postulated by some theories (Falkenstein et al., 1999; Gehring et al., 1993). Our results imply that while P3 may signal the engagement of working memory updating processes, its modulation by distractor type suggests a more selective role in cognitive operations, perhaps disputing its involvement in other postulated functions such as direct error signaling.

Task A, Distractor-elicited N2pc					**Task B, Target-elicited N2pc**				
Factor	**df**	**F**	**p**	**$\eta^2 p$**	**Factor**	**df**	**F**	**p**	**$\eta^2 p$**
Response speed	1	0.361	0.555	0.018	**Response speed**	1	7.523	**0.013**	0.273
Distract_type	4	15.352	**< .001**	0.434	**Distract_type**	4	12.964	**< .001**	0.393
Response speed ✻ Distract_type	4	1.129	0.349	0.053	**Response speed ✻ Distract_type**	4	0.206	0.934	0.01

Table 1. ANOVA Results for N2pc

	Fz, N1 (50–150 ms)				Fz, N2 (230–310 ms)				Fz, P3 (330–430 ms)			
Factor	df	F	p	η^2p	df	F	p	η^2p	df	F	p	η^2p
Target_location	1	0.005	0.943	2.625×10-4	1	2.342	0.142	0.105	1	1.337	0.261	0.063
Fast_Slow_trials	1	24.005	< .001	0.546	1	9.774	0.005	0.328	1	6.572	0.019	0.247
Distractor_type	4	39.974	< .001	0.667	2.524	24.838	< .001	0.554	2.624	3.272	0.034	0.141
Target_location✻ Fast_Slow_trials	1	0.008	0.929	4.075×10-4	1	0.229	0.637	0.011	1	0.027	0.872	0.001
Target_location✻ Distractor_type	4	0.888	0.475	0.043	4	0.607	0.659	0.029	4	1.599	0.183	0.074
Fast_Slow_trials✻ Distractor_type	4	1.426	0.233	0.067	4	3.34	0.014	0.143	4	1.839	0.129	0.084
Target_location✻ Fast_Slow_trials✻ Distractor_type	4	1.735	0.151	0.08	4	1.074	0.375	0.051	4	0.165	0.955	0.008

	Pz, N1 (50–150 ms)				Pz, N2 (230–310 ms)				Pz, P3 (330–430 ms)			
Factor	df	F	p	η^2p	df	F	p	η^2p	df	F	p	η^2p
Target_location	1	4.378	0.049	0.18	1	2.626	0.121	0.116	1	9.113	0.007	0.313
Fast_Slow_trials	1	21.322	< .001	0.516	1	0.275	0.605	0.014	1	27.369	< .001	0.578
Distractor_type	4	14.994	< .001	0.428	4	47.499	< .001	0.704	4	29.671	< .001	0.597
Target_location✻ Fast_Slow_trials	1	6.126× 10-4	0.98	3.063×10-5	1	6.971	0.016	0.258	1	0.14	0.712	0.007
Target_location✻ Distractor_type	4	1.193	0.32	0.056	4	0.453	0.77	0.022	4	0.712	0.586	0.034
Fast_Slow_trials✻ Distractor_type	4	0.652	0.627	0.032	4	1.574	0.189	0.073	4	0.442	0.778	0.022
Target_location✻ Fast_Slow_trials✻ Distractor_type	4	0.43	0.786	0.021	4	0.691	0.601	0.033	4	1.146	0.341	0.054

Table 2. ANOVA Results for ERP Components at Fz and Pz Electrode Sites. The table provides the outcome of a three-way repeated measures ANOVA for distinct ERP components measured at Fz and Pz electrode sites across different time intervals (N1, N2, and P3). Factors encompass 'Target location' (Task A vs. Task B), 'Response speed' (fast and slow trials), and 'Distractor type' (TO, SF, DC, DCS, and CM).

Chapter 4: Attentional Engagement with Task-Irrelevant Distractors: A Cross-Modal EEG Study

Attentional Engagement with Task-Irrelevant Distractors: A Cross-Modal EEG Study

Shao-Yang Tsai, Jan Nasemann, Hermann Müller and Zhuanghua Shi

Ludwig-Maximilians-Universität München, 80802 München, Germany

Author Note

This work was supported by the German Research Foundation (DFG) grants TO 940/1-2, awarded to ZS, respectively. Correspondence concerning this article should be addressed to Shao-Yang Tsai, Allgemeine und Experimentelle Psychologie, Department Psychologie, LMU München, Leopoldstr. 13, D-80802 Munich, Germany. Email: shaoyangtsai@gmail.com

Abstract

We are often distracted by things irrelevant to the task at hand, and much debate surrounds how we deal with this attentional capture on a neurological level. Some researchers suggest that we proactively suppress these distractors to avoid being captured by them, while others suggest we simply disengage from them quickly or don't engage with them at all. To understand these mechanisms better, here we conducted two experiments on visual search with visual-tactile items, with EEG recording. We varied the type of distractors, from inter-dimension (same as target), across-dimension (different color/shape from target), and across-modality (tactile vibrations), and their locations (middle vs. lateral sides) and the distractor-target stimulus onset asynchrony (SOA, 50 vs. 150 ms). We found that intra-dimension distractors caused the most interference in reaction time, while cross-dimension distractors induced minor interference, and cross-modality distractors did not affect search performance. Distractor-target similarity determines the degree of attentional engagement, as reflected by varied amplitudes of N2pc. Interestingly, the amplitude pattern of P_D mirrored the pattern of N2pc for the distractor-target 50 ms SOA condition. When the SOA prolonged to 150 ms, the amplitude of P_D leveled off for all three visual distractor conditions. Our findings suggest that distractors with target-relevant features deteriorate performance due to top-down attentional engagement. The longer distractor exposure further amplified the interference effects. And we propose that the P_D component reflects the degree of attentional disengagement, rather than the degree of reactive suppression.

Keywords: Dimension-weighting account (DWA), attentional engagement, distractor suppression, N2pc, P_D.

4.1 Introduction

Attentional control allows us to selectively focus on important stimuli while avoiding distractions in a sensory-rich environment. To illustrate, consider an everyday scenario - an important online meeting on your computer. Although you try to focus on the discussion within the Zoom window, a number of distractions, such as email notifications, WhatsApp messages, or even the subtle vibration of your cellphone, capture your attention. Despite these disruptions, the task at hand requires you to ignore these stimuli and concentrate on the ongoing meeting. However, it is well documented that despite top-down guidance, salient but irrelevant stimuli can inadvertently capture our attention (e.g., Theeuwes 1992, 2010). The question that arises from this is: how do we effectively handle distractions? Numerous theories propose distinct strategies to deal with such distractions. Some theories emphasize proactive suppression strategies like the signal-suppression account, which advocates for proactively suppressing task-irrelevant distractors in advance to avoid attentional capture (e.g., Gaspelin, Leonard, and Luck 2015; Gaspelin and Luck 2018b), or the dimension-weighting account (e.g., Found and Müller 1996; Liesefeld et al. 2019), which suggests modulating the weights of specific dimensions or modalities in order to lessen distraction salience. Non-engagement, a strategy that reduces attentional allocation to the distractor (e.g., Zivony and Lamy 2016, 2018; Zivony et al. 2018), could also be a way to reduce interference. In contrast, other theories highlight reactive strategies such as fast disengagement, where irrelevant distractors initially capture attention, but disengagement from them is expedited (e.g., Theeuwes 2010; Belopolsky and Theeuwes 2010; Theeuwes, Bogaerts, and van Moorselaar 2022). In this study, we adopt a more open perspective in examining proactive and reactive suppression. We propose that these two forms of suppression may coexist, however, their exact temporal progression and corresponding ERP indices need to be further elucidated.

It would be possible that these proactive and reactive suppression strategies are not mutually exclusive; both can occur during the attentional control process. The temporal attributes of stimulus presentation may play a crucial role in modulating these processes. In our previous study (Tsai et al., 2023b), we focused on the proactive suppression mechanism (Geng 2014; van Moorselaar and Slagter 2020; Theeuwes, Bogaerts, and van Moorselaar 2022), showing that it led to reduced engagement with distractors due to the down-weighting effect. In this study, we shift our focus to reactive suppression mechanisms and explore how this form of suppression interacts with attentional disengagement. We aim to elucidate the temporal dynamics of attentional control by manipulating the stimulus onset asynchrony (SOA) between the target and distractor stimuli, a factor that we believe plays a pivotal role in shaping our attentional response to distractions. This approach allows us to isolate specific attentional processes and examine how engagement and disengagement of attention unfold over time, providing valuable insights into the temporal dynamics of attentional control. Previous studies (Kastner and Ungerleider 2001; Beck and Kastner 2005; Kastner et al. 1998; Mathôt, Hickey, and Theeuwes 2010) have shown that the bias competition would reduce if stimuli are presented sequentially. By Manipulating the SOA between the target and distractor stimuli, we can observe attentional engagement and disengagement without the confound of strong resource competition between the target and distractor. Our exploration aims to unravel the intertwined relationship between temporal aspects of attentional engagement and disengagement and the neural underpinnings governing distraction processing.

Theoretical accounts such as the Dimension-Weighting Account (DWA, Found and Müller 1996; Müller, Reimann, and Krummenacher 2003; Liesefeld and Müller 2019) and the Modality-Weighting Account (MWA, see Figure 1A, Nasemann et al. 2023; Töllner et al. 2009) provide frameworks for understanding how top-down control may influence the processing of distractors in a proactive suppression manner (Sauter et al. 2021; Tsai et al. 2023; Qiu et al. 2023). They propose that attentional weights are allocated to the relevant dimensions or modalities of the target stimulus (i.e., up-weighting), while irrelevant dimensions or modalities are down-weighted, hence reducing the salience of distractions. In line with these theories, we posit that the manipulation of SOA, in combination with the weighting of attentional resources, will modulate our engagement with and disengagement from distractions, as reflected in the key event-related lateralization (ERL) components: (Negative posterior contralateral, also referred to PCN; e.g., Eimer 1996; Luck and Hillyard 1994b; Sawaki and Luck 2010; Hickey, Di Lollo, and McDonald 2009; Luck and Hillyard 1994a; Töllner, Müller, and Zehetleitner 2012; Töllner et al. 2011) (N2pc, also referred as to PCN) and distractor positivity (P_D) components.

N2pc is thought to be associated with the allocation of spatial attention (Negative posterior contralateral, also referred to PCN; e.g., M. Eimer 1996; Luck and Hillyard 1994b; Sawaki and Luck 2010; Hickey, Di Lollo, and McDonald 2009; Luck and Hillyard 1994a; Töllner, Müller, and Zehetleitner 2012; Töllner et al. 2011). If successful down-weighting occurs, distractions should mitigate performance, implying that they are more effortlessly ignored. This could manifest as a reduced distractor-elicited N2pc amplitude, signifying diminished attentional allocation. Another critical component is the P_D (distractor positivity) component, typically appearing between 300-450 ms after stimulus onset. The P_D component is assumed to be associated with distractor suppression (Hickey, Di Lollo, and McDonald 2009; Sawaki and Luck 2010; Feldmann-Wüstefeld and Vogel 2019; Gaspar and McDonald 2014; Sawaki, Geng, and Luck 2012; Gaspelin and Luck 2018a; Burra and Kerzel 2013; Barras and Kerzel 2016, 2017). If P_D represents the level of reactive distractor suppression, we would expect to see the increase in P_D amplitude might indicate an augmented effort in distractor suppression, especially in the condition that the huge engagement with the distractor happened.

This leads us to delve into the heart of our inquiry – the ambiguity surrounding the precise role of the P_D. Earlier studies have suggested that lateral distractors elicit a significant P_D, attributing P_D to distractor suppression. However, a more rigorous examination reveals complexities. Particularly, certain studies (e.g., Sawaki and Luck 2011; Gaspelin and Luck 2018a; Gaspar and McDonald 2014; Sawaki and Luck 2010; Kerzel and Huynh Cong 2023) indicated a P_D, with no significant N2pc preceding it. This could be seen as suggestive of proactive suppression. Conversely, some studies reported another P_D following a significant N2pc, indicating that proactive suppression might not have been effective and that attention was engaged with the lateral distractors (e.g., Liesefeld, Liesefeld, and Müller 2022; Tsai et al. 2018; Liesefeld et al. 2017; Feldmann-Wüstefeld, Weinberger, and Awh 2021; van Moorselaar and Slagter 2019). Upon engagement, it is plausible to observe a disengagement from the distractor if participants need to re-orient to the target. This raises the question of whether the late P_D genuinely reflects distractor suppression, or if it indicates a shift of attention away from the distractor. This ambiguity intensifies when considering the late P_D, which appears after the N2pc. Given that N2pc is associated with attentional engagement, the late P_D could signify attentional disengagement or a shift away from the distractor.

In our prior investigations (Tsai et al., 2023a; Tsai et al., 2023b), we found that lateral visual distractors triggered a significant N2pc, indicative of attentional engagement with the distractor. Intriguingly, we did not observe a significant P_D following the N2pc. As P_D is traditionally associated with distractor suppression, its absence, in spite of the manifest attentional engagement, prompted us to reevaluate its role. Could it be that P_D, rather than signifying distractor suppression, is indicative of attention re-orienting from the lateral distractor to the target? Furthermore, when the visual stimuli, both target and distractor, are presented for short durations, less than 250 ms in some previous studies (e.g., Tsai et al. 2023; Corriveau et al. 2012); Tsai et al., 2023b), the subsequent blank screen might not necessitate any attentional shift, hence the absence of P_D. To explore this alternative interpretation, our current study deliberately maintains the target on the screen until a response is made. This design alteration allows for opportunities to reevaluate the function of P_D and test its potential role in re-orienting attention.

The Rationale of Experiment Design

In the current research, we varied the distractor-target SOA, a temporal construct prevalent in past contingent capture paradigms, to delve into the temporal dynamics of attentional engagement and disengagement, as well as to scrutinize the neural mechanisms that govern distractor processing. Particularly, we employed the distractor-target SOAs of 50 ms and 150 ms in this investigation (further details are elaborated in the method section). Drawing upon past studies (e.g., Tsai et al., 2023a; 2023b), we observe that 50 ms roughly corresponds to the commencement of the Ppc component, which indicates signal registration. Conversely, 150 ms aligns with the onset of the N2pc component, signifying attentional engagement. Thus, the key distinction between these two SOAs lies in the phase of attentional engagement. By this manipulation, we aspire to elucidate the unique patterns and functions of the N2pc and P_D components, both of which play critical roles in the mechanics of attentional control.

For the manipulation of target-distractor similarity, the search target (a blue triangle) remains constant, while one of three types of visual distractors is displayed (excluding the target-only baseline condition). It is important to note that target positions are pre-set to appear either at the midline (above or below the fixation point in Task A) or laterally (to the left or right in Task B). This arrangement guarantees the absence of spatial overlap between the target and the distractors, thereby enabling a precise ERL analysis of attentional engagement and disengagement.

Additionally, our experiment takes a distinctive approach by integrating high-frequency tactile vibrations, which have traditionally been utilized as distractors (Tsai et al., 2023a; 2023b). Contrarily, in the current study, tactile vibrations are ingeniously employed as alerting cues, signifying the imminent appearance of a visual target. This design incorporates principles from the Modality-Weighting Account and builds upon the attentional network paradigm, notably the Attention Network Test (ANT)[16] formulated by Fan et al. (2002). Central to the Cross-Modal (CM) condition is the interplay between intense (high-frequency) tactile vibrations and their temporal relation to the target presentation. The tactile cues, regardless of intensity, precede the target by either 550 ms or 650 ms. However, intense (high-frequency vibration) tactile cues are presented infrequently, constituting only 20% of the task trials (note: 80% trials with weak vibrations, see method section for the details), thereby creating a scenario akin to an 'oddball' paradigm where a small number of trials with deviant stimuli tend to capture more attention. This design aims to ascertain if the sparse and temporally-proximate presentation of tactile vibrations can enhance the attentional system, making participants more vigilant and primed to react to the visual target. If the tactile modality is down-weighted in line with the MWA, we would expect this oddball effect to disappear, implying no discernible difference between high and low-frequency vibration conditions.

We weave into our examination the contrast between proactive and reactive suppression, as guided by the DWA/MWA. DWA/MWA posits that up/down-weighting mechanisms function within the context of proactive suppression. Yet, in the present study, we strategically manipulated the SOA to allow the distractor to manifest initially in isolation, thus questioning the efficacy of proactive suppression since the distractor may succeed in capturing attention. Particularly in our prior research (Tsai et al., 2023b), where we simultaneously presented the target and distractors, this design could diminish the attentional capture of the distractor, offering fewer instances to witness the possible processes of reactive suppression. Moreover, despite the pivotal function of proactive suppression congruent with DWA, it may appear insufficient in wholly protecting us from attentional capture by the distractor, resulting in the N2pc components displaying engagement with the distractors (even for the nontarget feature distractors). We also conjecture that proactive and suppressive mechanisms can operate concurrently during distractor processing. Hence, our attention now turns to exploring the operation of reactive suppression. However, the role of P_D may not mirror the attentional interplay with distractors in a linear fashion, potentially signaling an attentional shift rather than a simple act of distractor suppression.

[16] In ANT, three networks of attention—alerting, orienting, and executive control—are measured by looking at the reaction time (RT) difference in response to various cues and targets. Alerting cues are used to inform the participant about the impending target, while spatial cues are used to guide attention toward the target location. The third part of the ANT involves testing executive control by introducing conflicting information, such as incongruent flankers (e.g., > > < > >) or congruent flankers (e.g., < < < < <). Participants should respond to the direction of the middle arrow.

4.2 Method

Participants

26 right-handed undergraduate students were recruited for this investigation. Due to technical complications and excessive EEG artifacts, six participants were excluded. The final cohort consisted of 20 participants (5 females) with a mean age of 29 years (SD = 3.5; range 22-36 years). Participants were screened for a history of neurological or psychiatric disorders and provided written informed consent. The Ethics Committee of the LMU Psychology and Educational Sciences approved the study protocol. Participants received financial compensation at a rate of 9 euros per hour for their participation.

Experimental Procedure

Participants participated in two visual discrimination tasks, Task A and Task B, inside a dimly lit, sound-attenuated chamber (see Figure 1). Their primary objective was to discriminate the orientation of a blue triangular target (either pointing upwards or downwards) as fast as possible and as accuracy as possible. Participants were explicitly instructed regarding the potential locations of the targets and were advised to disregard other locations. Prior to the commencement of each task, participants undertook a practice run comprising 20 trials to acclimate to the task, with the stipulation that their accuracy surpass 80%. Should their accuracy fall below 80%, an additional practice run was administered. Most participants only needed one practice session to meet the accuracy requirement. No participant required more than two practice sessions. Each task was subdivided into four blocks, with each block encompassing 200 trials, cumulating to 800 trials per task. Brief breaks were allotted after every 35 trials within each block. The sequence of task execution (either AB or BA) was counterbalanced amongst participants. The estimated duration for each task was approximately 35 minutes.

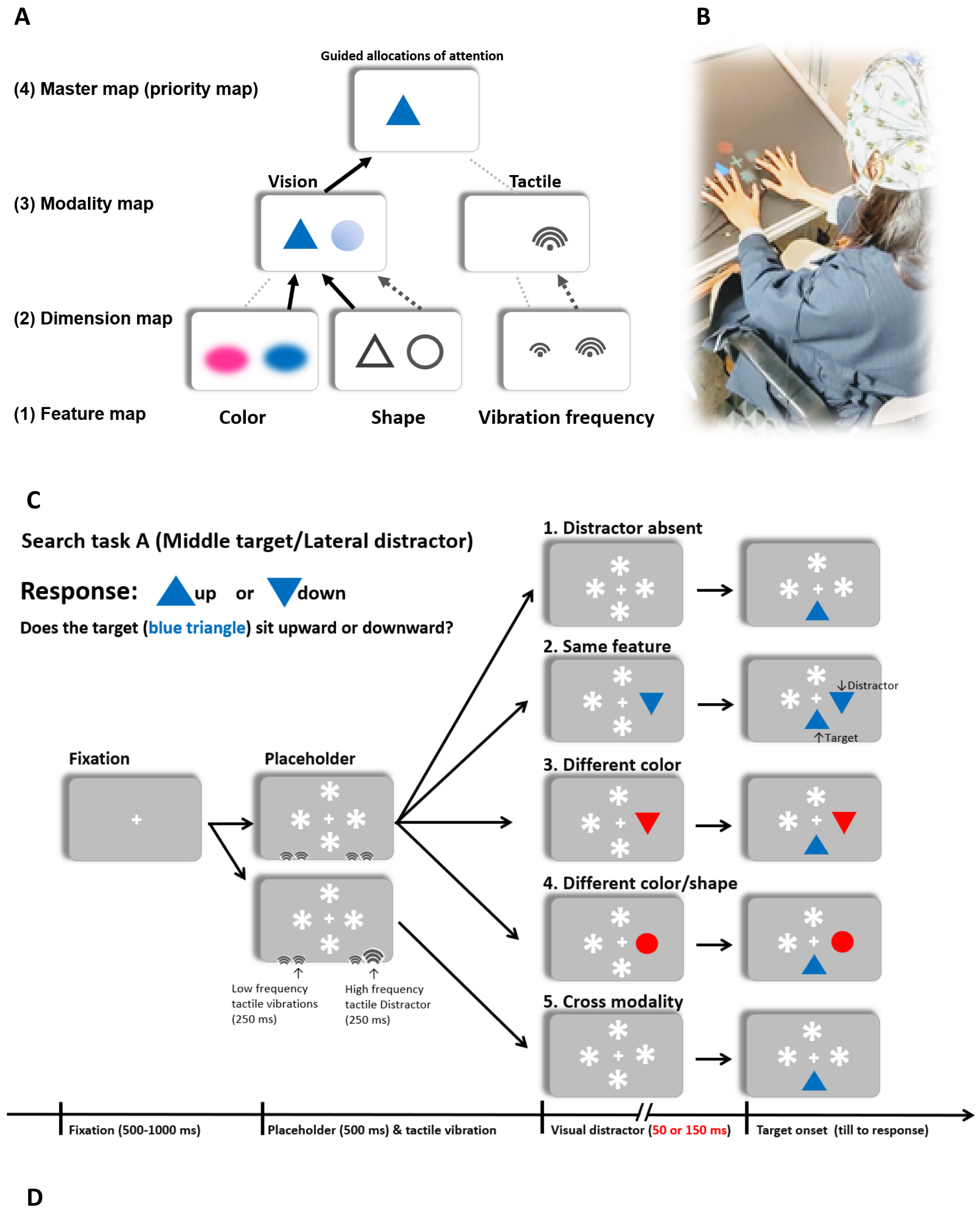
Stimuli and Task Design

The visual stimuli were projected through a rear projector (Sharp XR-32X-L) onto a semi-transparent Plexiglas surface (window dimensions: 38.1 degrees x 12.5 degrees) slanted approximately 60 degrees toward the participant. The stimuli were restricted to four distinct spatial coordinates (left, right, top, bottom) at an eccentricity of 5.2° of visual angle. Tactile stimuli were delivered via solenoids situated directly beneath the visual elements and channeled through a 10-channel amplifier to the solenoid actuators (Dancer Design), each solenoid measuring 1.8 cm in diameter. The visual hues (blue, red, and white) were maintained at equal luminance (36 cd/m^2), and tactile amplitudes were kept the same (40 Hz or 100 Hz). To reduce auditory interference generated by the tactile stimulations, participants wore headphones (Philips SHL4000, 30-mm speaker drive) that played pink noise at 65 dBA during the stimulus presentation.

Task A and Task B employed two distinct visual discrimination paradigms (refer to Figure 1C and 1D). In Task A, the target was centrally aligned (top or bottom), with a lateral distractor. In Task B, the target appeared laterally, and the distractor was centrally aligned. We incorporated five distractor variations: Same-Feature (SF), Different-Color (DC), Different-Color and Shape (DCS), Target-Only (TO), and Cross-Modality (CM). The SF, DC, and DCS conditions included visual distractors, whereas the TO and CM conditions consisted solely of placeholders, lacking visual distractors. Each trial began with a fixation interval for random 500 to 1000 ms.

Following the fixation interval, placeholders (*) were displayed for 500 ms. Concurrently, tactile stimuli were introduced for a shorter duration of 250 ms, meaning that while the placeholders remained visible for the entire 500 ms, the tactile stimuli were only present for half of that time. In the conditions with visual distractors (SF, DC, and DCS), a distractor was presented first. Then, after a stimulus onset asynchrony (SOA) of either 50 ms or 150 ms, the visual target was displayed and remained on screen until the participant responded using a foot pedal. (Note: for the TO and CM conditions, participants only saw the placeholders.)

Previous research indicated that cross-modal distractors, with a few fingers stimulated at 100 Hz and the remaining fingers at 40 Hz, did not adversely impact the visual identification performance of the participants (e.g., Tsai et al., 2023a; 2023b). This observation may be explained by the effective suppression of the tactile modality, consistent with the modality-weighting hypothesis. Differing from previous studies, the current investigation utilizes high-frequency tactile stimuli akin to an “alert cue” rather than as distractors. This cue (placeholder) is orchestrated to inform participants of the impending presentation of the target, where tactile vibrations precede the target display by either 550 ms or 650 ms. The Cross-Modality (CM) condition serves as an “anomalous condition”, akin to the oddball paradigm, where high-frequency vibration conditions arise sporadically, accounting for 20% of the task trials. This is intended to evaluate whether this configuration augments alertness and preparedness in response to the visual target. The design of this study is also influenced by the Attention Network Test (ANT) by Fan et al. (2002), particularly concerning the incorporation of an alerting cue. In ANT, alertness is quantified by evaluating the reaction time (RT) disparity between the absence of a cue and the presence of dual cues. As per the Modality Weighting Account (MWA), the anticipated outcome is a down-weighting of the tactile modality, signifying that the CM condition does not intrinsically bolster preparedness for visual searching. In contrast, if the tactile modality is not down-weighted, it is expected that participants would manifest enhanced performance relative to the baseline condition (TO).



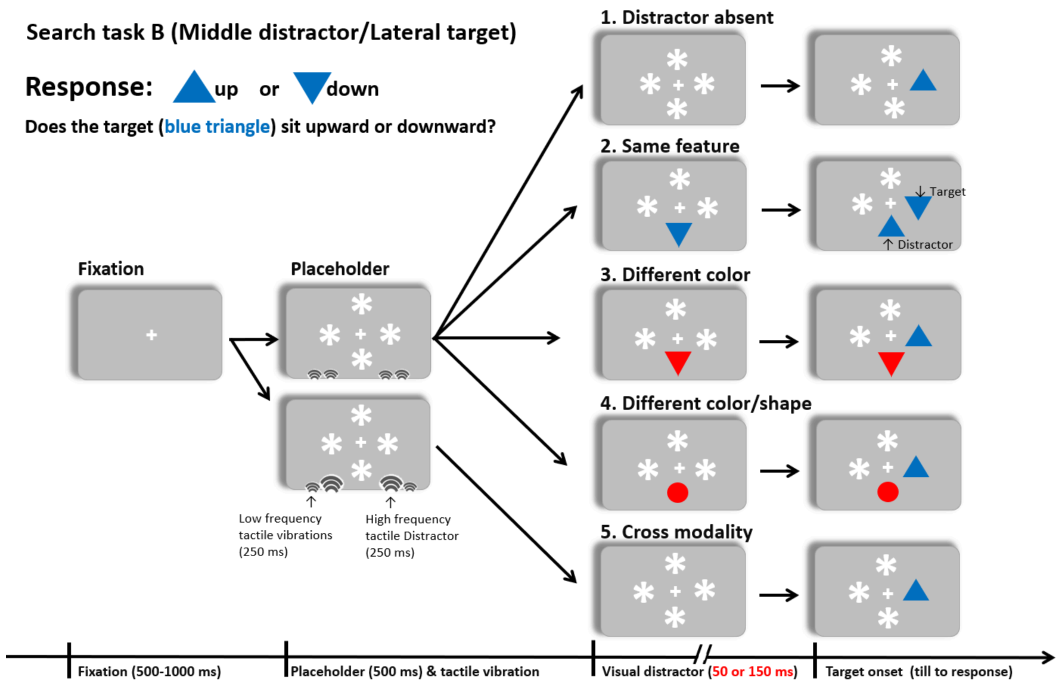


Figure 1. Conceptual Representation of the Experiment.

A. Figure 1. The hierarchical structure proposed by the modality-weighting account. The architecture is divided into four integral layers (Töllner et al., 2009): (1) At the base, the feature map layer aggregates raw sensory data; (2) Moving upward, the dimension map layer categorizes specific attributes such as color, shape, or vibration frequency; (3) The modality map layer follows, synthesizing features within individual sensory modalities (e.g., vision); (4) Culminating the hierarchy is the master or saliency priority map that merges all modality maps, resulting in a comprehensive sensory perception (e.g., integrating vision and tactile input). **B**. The participant is seated on a chair with each of their fingers positioned on one of ten tactile vibrators (solenoids). Visual stimuli are displayed above the solenoids. The target is invariably a blue square, and participants are required to indicate the orientation of the blue triangle (pointing up or down) by using foot pedals. **C and D**. Each trial begins with a 500-1000 ms fixation, succeeded by 500 ms placeholders, and culminating in the presentation of the search display (inclusive of tactile stimuli) for 200 ms. Task A mandates that the target is always centrally positioned (top or bottom), while in Task B, the target is located laterally (left or right).The task is divided into five conditions: 1. Target-only condition (TO). 2. Same-feature distractor (SF), characterized by a blue triangle that is oriented opposite to the target. 3. Different-color distractor (DC), featuring a red triangle with an orientation inverse to the target. 4. Different-color and different-shape distractor (DCS), presented as a red circle, differing from the target in both shape and color. 5. Cross-modality distractor (CM), wherein the distractor is a high-frequency vibration (100 Hz) emitted by four solenoids, in contrast to the low-frequency vibrations (40 Hz) produced by the other solenoids. In Task A, high-frequency vibrations are limited to the four lateral fingers of one hand, whereas in Task B, these vibrations occur symmetrically on the thumbs and index fingers of both hands

EEG Recording and Preprocessing

EEG signals were continuously recorded using a set of 64 Ag/AgCl active electrodes, as part of the acti-CAP system from Brain Products Munich, which were linked to a BrainAmp Standard amplifier. These signals were sampled at a rate of 1000 Hz in accordance with the international 10-20 system, with an active reference electrode situated at Fcz. For preprocessing, EEGLAB v2020 (Delorme & Makeig, 2004) was utilized. The EEG data were re-referenced to the mastoid channels (TP9 and TP10) offline. An independent component analysis (ICA, extended infomax, Bell and Sejnowski 1995; Lee, Girolami, and Sejnowski 1999) was employed to identify and remove artifacts resulting from eye movements such as blinks and saccades. Post artifact removal, the data underwent high-pass filtering at 1 Hz and low-pass filtering at 25 Hz. The EEG data were then segmented into epochs of 2500 ms with reference to the onset of the tactile stimulus and baseline-corrected (from -200 to 0 ms) for each trial.

For in-depth analysis, electrodes PO7, PO8, C3, C4, Fz, Cz, and Pz were singled out since the study aimed to examine event-related lateralization triggered by lateral visual and tactile stimuli. Trials were discarded if they met any of the following criteria: amplitudes exceeding ±60 μV, peak-to-peak deflections larger than 100 μV, or flatlining within the -200 to 500 ms window for each epoch. Six participants were subsequently excluded due to more than 30% of their trials in one condition being rejected. Among the remaining participants (n=20), the average rejection rate for invalid trials was around 5% for both Task A and Task B. Once the invalid trials were removed, only trials with correct responses were included in the ERP analysis.

Statistical Analysis

JASP software (version 0.16.4.0, 2021) was utilized to perform statistical analyses on both behavioral and ERP data. Repeated measures ANOVAs were conducted, and when the sphericity assumption was not met, the Greenhouse-Geisser correction was employed. For post hoc multiple comparisons, Holm tests were applied.

Participants were directed to give equal emphasis to response speed and accuracy, though reaction time (RT) was the primary behavioral metric in this study. To ensure reliable and representative RT data for subsequent analyses of event-related potentials (ERPs) and event-related lateralizations (ERLs), specific inclusion criteria were established. Only trials with correct responses and RTs between 250 ms and 1000 ms, approximately within two standard deviations from the mean, were included. This led to the exclusion of less than 5% of the total trials, with the maximum rejection rate for individual trials being 4%.

In this study, we concentrated on several key ERL components and examined their interplay with our experimental tasks. Firstly, we focused on the N2pc component, widely recognized as a significant marker for attentional engagement (e.g., Eimer 1996; Sawaki and Luck 2014; Luck 2011; Luck and Hillyard 1994b; Woodman and Luck 1999; Woodman and Luck 2003; Sawaki and Luck 2010). Secondly, we examined the Ppc component, which is associated with early sensory processing (Störmer, McDonald, and Hillyard 2009; Woldorff et al. 1997; e.g., Itthipuripat et al. 2014; Luck and Hillyard 1994a; Tsai et al. 2023). In addition, we looked into the P_D component, linked to distractor suppression (e.g., Feldmann-Wüstefeld, Uengoer, and Schubö 2015; Feldmann-Wüstefeld and Schubö 2013; Hilimire and Corballis 2014; Gaspar and McDonald 2014). Lastly, we incorporated the CCN component, reflected in the C3/C4 electrodes, which signifies tactile processing (Forster, Tziraki, and Jones 2016; Eimer et al. 2004; Eimer and Driver 2000; Töllner et al. 2009; Tsai et al. 2023). Given the distinct lateralizations in Task A (distractor-elicited) versus Task B (target-elicited), we present the ERL results separately.

The components N2pc, Ppc, and P_D were extracted from the parieto-occipital electrodes (PO7/PO8). Given the variability in peak latencies across components and among participants, a peak detection approach was implemented for ERL analysis. After calculating the difference waves for individuals, the time points of maximal and minimal voltage values were identified within designated windows for each component. In Task A, the windows were 550-700 ms (note: the visual distractor onset is 500 ms) for Ppc, 650-800 ms for N2pc, and 700-900 ms for P_D. In Task B, the peak detection windows were adjusted: 550-700 ms for short SOA and 650-800 ms for long SOA for target-elicited Ppc; 550-700 ms for short SOA and 650-800 ms for long SOA for target-elicited N2pc. The mean amplitudes were then averaged around each peak time point (±10 ms) for each participant.

For each ERL component, a repeated-measures ANOVA was carried out with SOA and Distractor as factors. In Task A's TO condition, the target appeared centrally and no lateral distractors were present, so no lateralization waves were expected. To utilize the TO condition as a baseline against other distractor types, "pseudo-distractors" were randomly assigned to 50% of the TO trials on either the left or right side, even though they were not visible to participants. This allowed for the calculation of difference waves. As anticipated, the difference wave for the TO condition in Task A was almost flat, nearing 0 μV.

4.3 Results

Behavioral results

In Figure 2 (A and B), the correct mean RTs are shown for different types of distractors, separated for two SOAs (lines) and two tasks (left vs. right panel). A three-way repeated-measures analysis of variance (ANOVA) was employed, considering the factors of Target Location (Task A versus Task B), SOA (50 ms vs. 150 ms), and Distractor Type (TO, SF, DC, DCS, and CM) on the mean RTs. The analysis revealed a significant main effect for Target Location, $F(1, 19) = 5.692$, $p = .028$, $\eta_p^2 = 0.231$, Distractor Type, $F(4, 76) = 134.537$, $p < .001$, $\eta_p^2 = 0.876$, and SOA, $F(1, 19) = 8.944$, $p = .008$, $\eta_p^2 = 0.320$. Moreover, a significant two-way interaction was observed between SOA and Distractor Type, $F(4, 76) = 9.653$, $p < .001$, $\eta_p^2 = 0.337$. The other interactions were not significant, Fs <1.73, ps > .16, η_p^2 s< 0.084.

Subsequent post hoc tests for Distractor Type ascertained that the same-feature (SF) distractor condition exhibited the slowest RT. Notably, the SF condition surpassed the different color (DC) condition by a mean difference of 27 ms ($p < .001$), the different color and shape (DCS) condition by a mean difference of 48 ms ($p < .001$), the cross-modality (CM) condition by a mean difference of 55 ms ($p < .001$), and the target-only (TO) condition by a mean difference of 52 ms ($p < .001$). Additionally, the DC condition exhibited longer RTs compared to the DCS condition by a mean difference of 21 ms ($p < .001$), the CM condition by a mean difference of 28 ms ($p < .001$), and the TO condition by a mean difference of 25 ms ($p < .001$). The DCS condition demonstrated a trend toward longer RTs compared to the CM condition by a mean difference of 7 ms, although this trend did not reach statistical significance ($p = .060$). No significant differences were observed between the TO and DCS conditions ($p = .341$), nor between the TO and CM conditions ($p = .341$). These results underscore the significant influence of distractors sharing features with the target, as seen in the slowest reaction times in the same-feature (SF) condition. Conversely, different color/shape (DCS) and different-color (DC) conditions lead to faster responses, reflecting less interference.

Furthermore, the impact of Distractor Type on RTs was contingent upon SOA, corroborated by the significant interaction between SOA and Distractor Type (see Figure 2E). RTs for the TO, DCS, and CM conditions were expedited when the SOA was extended to 150 ms, as opposed to 50 ms (Mean Differences > 9 ms, *p*s < 0.042). This suggests that longer preparation intervals (SOA of 150 ms compared to 50 ms), potentially providing participants with more time to suppress the distractor, resulted in an enhancement of performance on the target. Intriguingly, the SF condition exhibited an opposite pattern to the other conditions, with responses lengthening when SOA was lengthened to 150 ms in comparison to 50 ms. The extended exposure to the distractor induced more pronounced interference exclusively when the distractor possessed features analogous to the target. Conversely, in the absence of target-like features (e.g., DCS condition), extended distractor exposure did not produce further interference. These results align with our expectation that distractors sharing features with the target (as in the SF condition) can effectively engage attention. The prolonged exposure to the distractor (longer SOA) might amplify this 'engagement', causing increased interference and longer reaction times.

The accuracy of responses was also assessed, as depicted in Figure 2 (C and D), which presents the mean accuracy rates. A separate three-way repeated-measures ANOVA on the mean accuracy rates revealed a significant main effect for Distractor Type, $F(4, 76) = 4.341$, $p = .003$, $\eta_p^2 = 0.186$. Post hoc comparisons for Distractor Type revealed that the DC condition showed a significantly lower accuracy rate compared to the TO condition (Mean Difference = 1.2%, $p = 0.03$) and the DCS condition (Mean Difference = 1.3%, $p = 0.01$). However, it is important to note that the magnitude of these differences in accuracy rates is relatively small. Furthermore, the main effects of Target Location and SOA did not reach statistical significance, $F(1, 19) = 1.803$, $p = .195$ for Target Location, and $F(1, 19) = 0.085$, $p = .774$ for SOA. Additionally, none of the two-way or three-way interactions amongst Target Location, SOA, and Distractor Type were statistically significant (*p*s > .05 for all interactions).

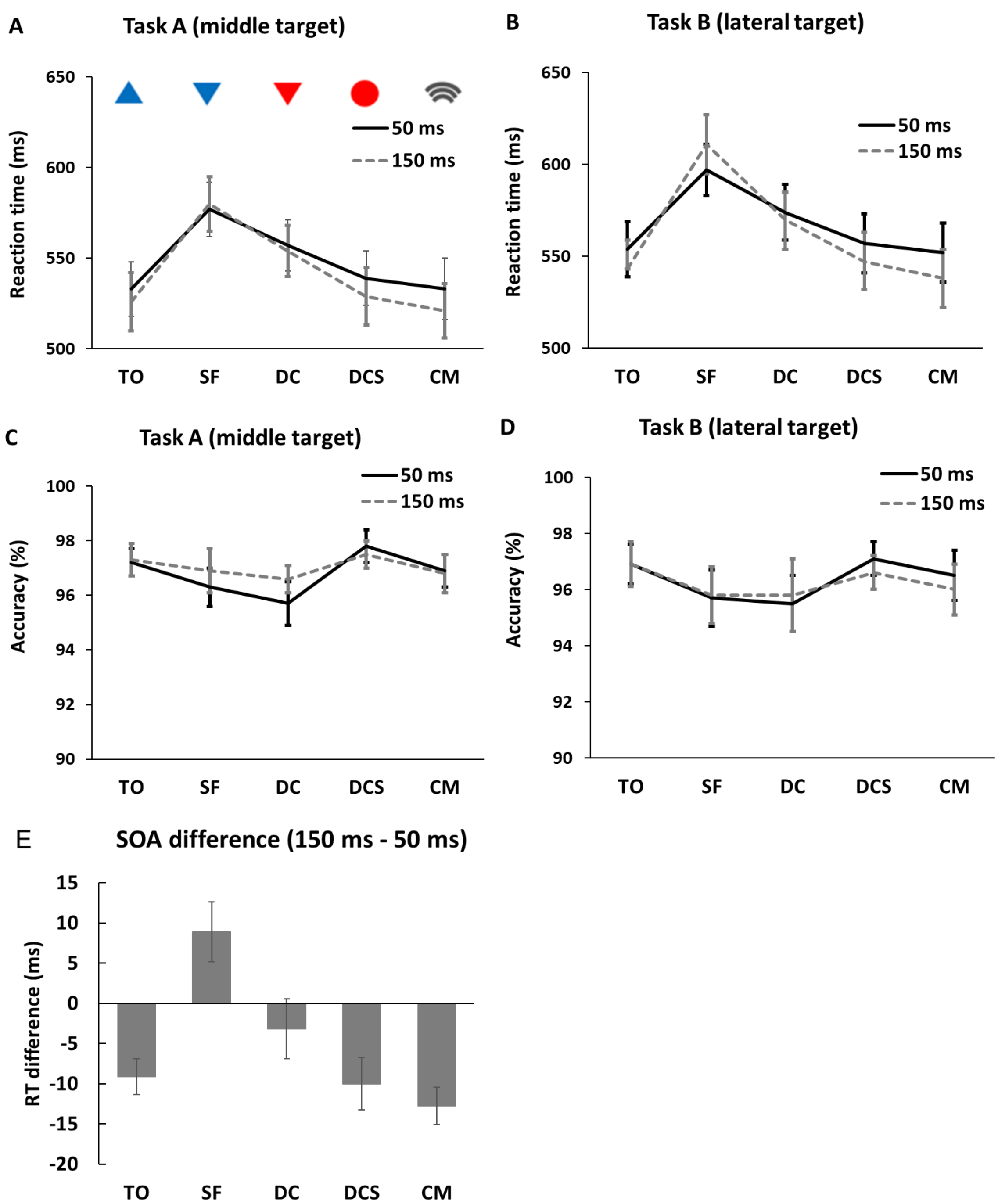


Figure 2. Behavioral results. Mean reaction times (A and B) and accuracy (C and D). Error bars represent the standard error of the mean. The search task encompasses five conditions: 1. Target-only condition (TO). 2. Same-feature distractor (SF) - a blue triangle with an opposite direction to the target. 3. Different-color distractor (DC) - a red triangle shape with the opposite direction to the target. 4. Different-color and different-shape distractor (DCS) - a red circle. 5. Cross-modality distractor (CM) - a vibrotactile distractor represented by

salient 100-Hz vibrations. E. RT Difference between SOAs (150ms - 50ms) across the five distractor types. Notably, the SF condition shows an inverse pattern compared to the other conditions

ERP results

Figure 3 represents event-related lateralizations (ERLs). We calculated difference waveforms as the difference between contralateral and ipsilateral responses to lateralized distractors in Task A and targets in Task B. Figure 4 illustrates the peak amplitudes for the Ppc, N2pc, and P_D components from PO7/PO8 electrodes.

Task A (Middle target/Lateral distractor): Distractor-elicited lateralization

Distractor-elicited Ppc (peak detection window: 50-200 ms after the lateral distractor onset. Note: visual distractor onset is 500 ms. Fig 4A left panel**).** The Ppc component is implicated in the early sensory processing of lateral stimuli, as substantiated by previous research (e.g., Störmer, McDonald, and Hillyard 2009; Woldorff et al. 1997; Itthipuripat et al. 2014; Luck and Hillyard 1994a; Tsai et al. 2023). In this study, paired-samples t-tests were employed to assess the significance of the Ppc peak amplitude in relation to the maximal amplitude observed during the baseline period (-200 to 0 ms). The tests showed that the Ppc peak amplitude surpassed the baseline maximum exclusively in the SF (for both SOA 50 and 150 ms), and DCS (for SOA of 50 ms only) (*p*s < .001) conditions.

Further, a two-way repeated-measures ANOVA, with SOA and Distractor Type as within-subject factors, was executed to probe the Ppc peak amplitude. This revealed a main effect of Distractor Type ($F(4, 76) = 9.134$, $p < .001$, $\eta_p^2 = 0.325$), but no main effect of SOA ($F(1, 19) = 1.098$, $p = .308$, $\eta_p^2 = 0.055$), and no interaction between SOA and Distractor Type ($F(4, 76) = 1.147$, $p = .341$, $\eta_p^2 = 0.057$) were detected. Subsequent post hoc analyses revealed that the Ppc peak amplitude was significantly enhanced in the Same-feature (SF) condition compared to the Target-only (TO) (Mean Difference = 1.044, $p < .001$), Different-color (DC) (Mean Difference = 0.766, $p = .003$), Different-color/shape (DCS) (Mean Difference = 0.678, $p = .009$), and Cross-modality (CM) (Mean Difference = 1.079, $p < .001$) conditions. There were no other significant effects in the post hoc tests. It is noteworthy that in the experimental paradigm, where the visual distractor was presented first before the target, an increased Ppc amplitude was observed only when the distractor had same target featrues.

Distractor-elicited N2pc (peak detection window: 150-300 ms after the lateral distractor onset. Figure 4A middle panel**).** Preliminary analyses were carried out to ensure that the N2pc peak amplitude was significantly elevated relative to the minimum value in the baseline window (200 - 0 ms) for the conditions of interest. Paired samples t-tests established that this was the case for the SF, DC, and DCS conditions at both 50 ms and 150 ms SOAs (all *p*s < .001), but not for the TO and CM conditions.

Following this confirmation, a 2×5 repeated-measures ANOVA showed a significant main effect of SOA ($F(1, 19) = 95.976$, $p < .001$, $\eta_p^2 = 0.835$), a significant main effect of Distractor Type ($F(4, 76) = 103.079$, $p < .001$, $\eta_p^2 = 0.844$), and, critically, a significant interaction between SOA and Distractor Type ($F(4, 76) = 13.42$, $p < .001$, $\eta_p^2 = 0.414$). Post hoc analyses elucidated that the N2pc peak amplitude was significantly larger at 150 ms relative to 50 ms (Mean Difference = 1.044, $p < .001$). Furthermore, within the Distractor Type, the SF condition showed a significantly elevated N2pc amplitude compared to the TO (Mean Difference = 4.646, $p < .001$), DC (Mean Difference = 0.956, $p = .004$), and DCS (Mean Difference = 2.264, $p < .001$) conditions. Additionally, substantial differences were detected between other Distractor Type conditions, such as DC and DCS (Mean Difference = 1.308, $p < .001$), and DC and CM (Mean Difference = 3.863, $p < .001$). These findings indicate that attentional capture was more likely to occur when distractors are presented alone longer prior to the target. Furthermore, distractors sharing more target features enhanced attentional capture and induced larger interference.

Distractor-elicited N2pc peak latency. This analysis was confined to the SF, DC, and DCS conditions, which reliably evoked the N2pc component (Fig 5 Left panel). We performed a 2×3 repeated-measures ANOVA on the N2pc peak latency data, with SOA and Distractor Type as factors. There was a significant main effect of Distractor Type ($F(2, 38) = 7.866$, $p = .001$, $\eta_p^2 = .293$). Post hoc comparisons revealed that the SF condition was associated with a significantly earlier N2pc latency compared to both the DC (Mean Difference = 12.85 ms, $p = .002$) and the DCS conditions (Mean Difference = 10 ms, $p = .011$). However, there was no latency difference between the DC and DCS conditions. The results showed a non-significant main effect of SOA on N2pc latency ($F(1, 19) = 1.999$, $p = .174$, $\eta_p^2 = .095$). The interaction between SOA and Distractor Type did not reach significance ($F(2, 38) = 0.122$, $p = .886$, $\eta_p^2 = .006$). The findings that attentional selection, as indicated by the N2pc latency, occurred earlier when distractors shared the same feature with the target relative to when distractors differed in color or both color and shape from the target, underscore the time-sensitive nature of attentional shifts.

Distractor-elicited P_D (peak detection window: 200-400 ms after the lateral distractor onset. Figure 4A right panel**).** A two-way repeated measures ANOVA showed a significant main effect of Distractor Type ($F(4, 76) = 67.373$, $p < .001$, $\eta_p^2 = .78$), but not of SOA ($F(1, 19) = 2.033$, $p = .17$, $\eta_p^2 = .097$). Importantly, a significant interaction between SOA and Distractor Type was found ($F(4, 76) = 4.421$, $p = .003$, $\eta_p^2 = .189$). The post-hoc analyses revealed that the P_D peak amplitude was significantly influenced by the Distractor Type. Specifically, the P_D amplitude for SF, DC and DCS had greater P_D amplitudes compared to TO (*p*s < .001). Furthermore, SF showed a larger P_D amplitude in comparison to DCS and CM (*p*s < .008). Additionally, DC and DCS displayed a higher P_D amplitude compared to CM (*p*s < .001).

For the SF and DC conditions, the analysis showed no significant differences in P_D amplitudes between the SOAs of 50 ms and 150 ms (*p*s > .05 for both). However, for the DCS Distractor Type, a significant discrepancy in P_D amplitudes was detected between the two SOAs ($p < .001$). Interestingly, at an SOA of 150 ms, P_D amplitudes were unexpectedly identical across all three Distractor Types (SF, DC, and DCS) (*p*s > .05 for all comparisons), suggesting that the duration of distractor exposure exerted a uniform effect across the distractor types.

We interpret this interaction of SOA×Distractor Type as meaningful for elucidating the functional role of the P_D component. Specifically, the similarity of P_D amplitudes across the three Distractor Types at an SOA of 150 ms implies that the P_D may not be exclusively representative of distractor suppression. It could also be indicative of a shift of attention away from the distractor, orienting towards the target, particularly under conditions of prolonged distractor exposure (150 ms). Contrastingly, at an SOA of 50 ms, the DCS Distractor Type appeared to exert a weaker pull on attention, as reflected in a relatively diminished P_D amplitude. This could potentially be attributed to a reduced need to shift attention away from a less attention-captivating distractor.

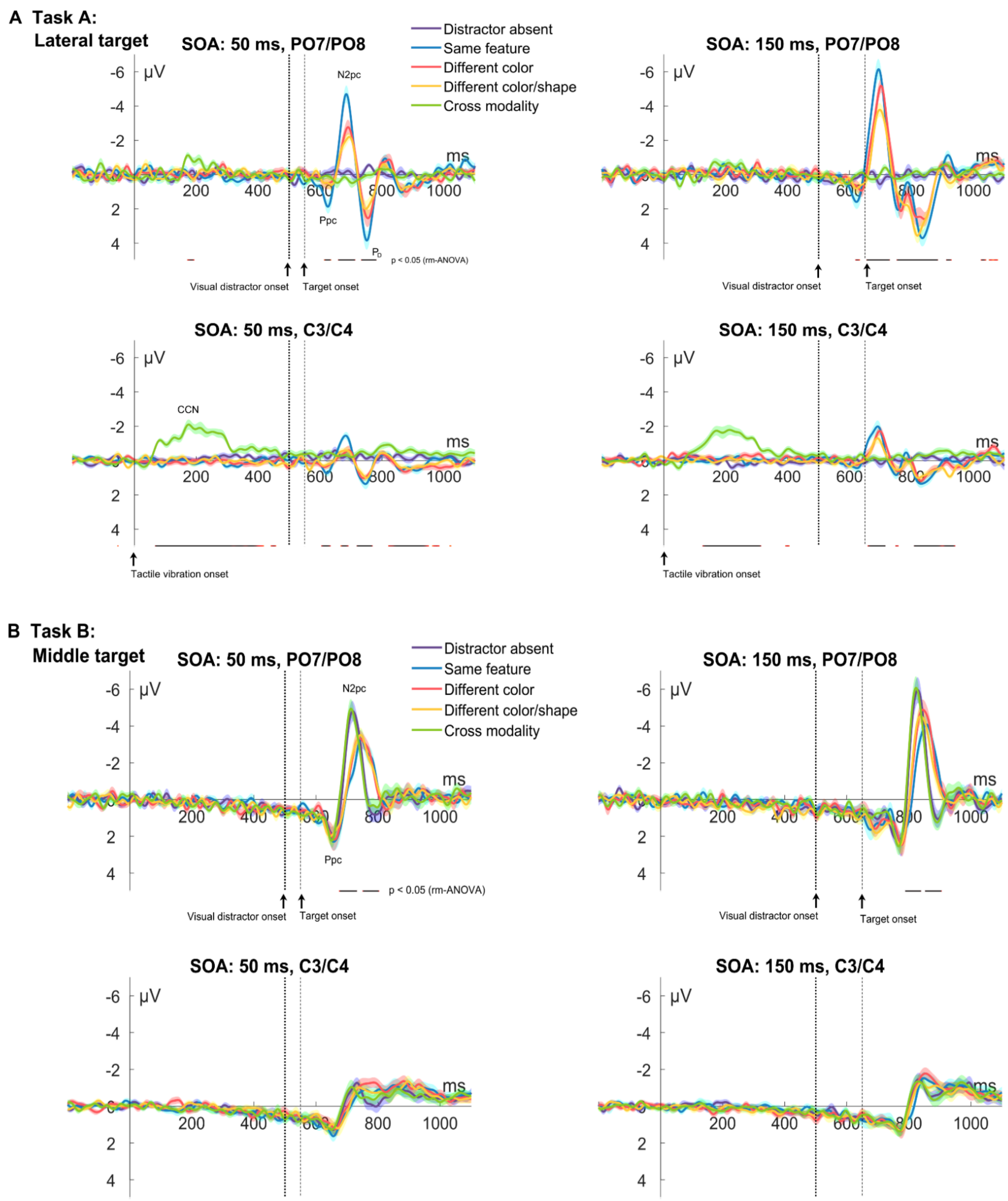
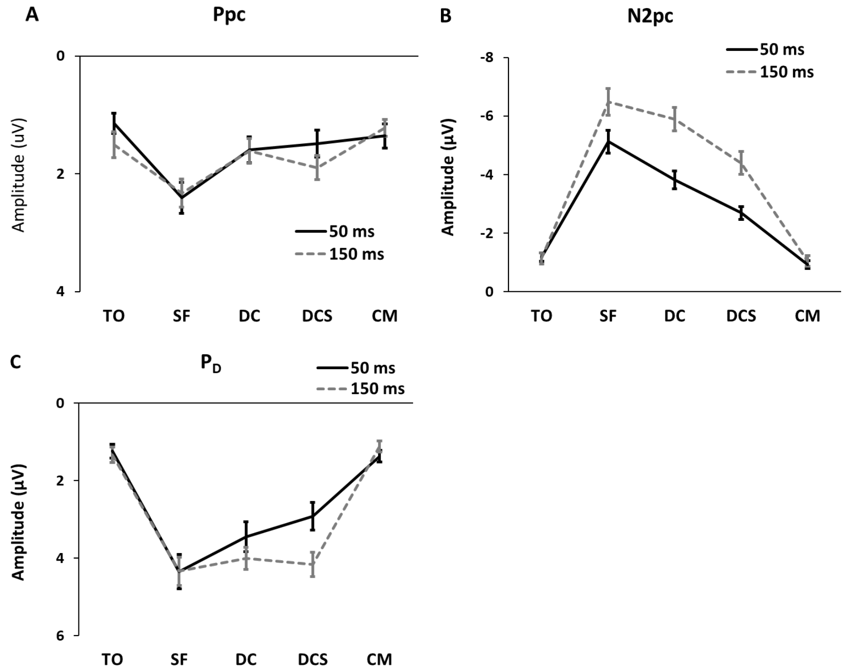


Figure 3. The ERL difference waveforms. The difference waveforms (contralateral minus ipsilateral waves) from PO7/PO8 (upper panel) and C3/C4 (lower panel). The shaded area on each waveform is the standard error of the mean.

A Task A: Middle target/lateral distractor



B Task B: Middle distractor/lateral target

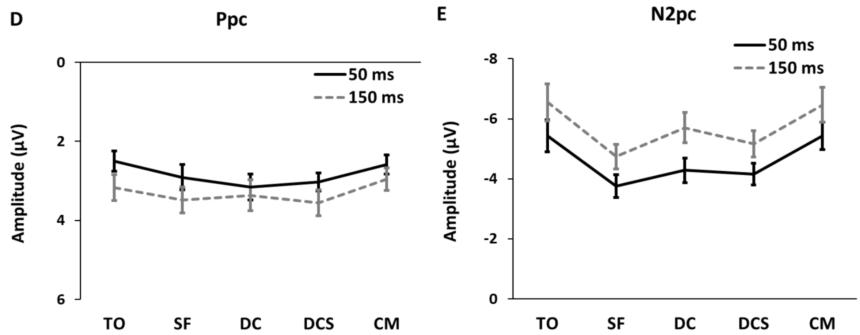


Figure 4. ***Peak amplitudes of difference waves***. Error bars represent the standard error of the mean. The search task encompasses five conditions: 1. Target-only condition (TO). 2. Same-feature distractor (SF) - a blue triangle with an opposite direction to the target. 3. Different-color distractor (DC) - a red triangle shape with the opposite direction to the target. 4. Different-color and different-shape distractor (DCS) - a red circle. 5. Cross-modality distractor (CM) - a vibrotactile distractor represented by salient 100-Hz vibrations.

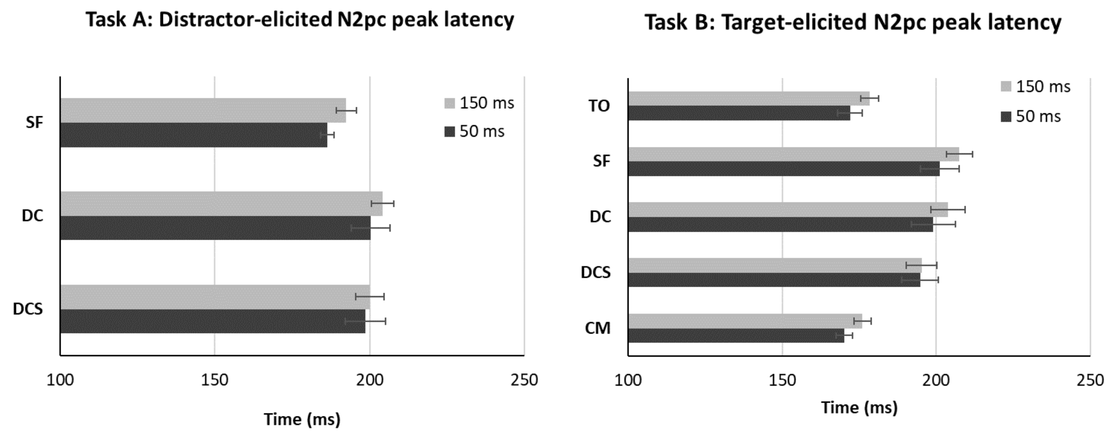


Figure 5. ***N2pc Peak latency***. Error bars represent the standard error of the mean. The search task encompasses five conditions: 1. Target-only condition (TO). 2. Same-feature distractor (SF) - a blue triangle with an opposite direction to the target. 3. Different-color distractor (DC) - a red triangle shape with the opposite direction to the target. 4. Different-color and different-shape distractor (DCS) - a red circle. 5. Cross-modality distractor (CM) - a vibrotactile distractor represented by salient 100-Hz vibrations.

Task B (Middle distractor/Lateral target): Target-elicited lateralization

In Figure 3, the upper panel portrays the ERL differential waveforms derived from PO7/PO8. A close visual analysis reveals that the target-induced N2pc amplitude occurs within the range of 600-700 ms when the SOA is 50 ms, and within 700-800 ms for an SOA of 150 ms. This is attributed to the fact that in Task B, the target is presented laterally. The lower panel of Figure 3 shows the ERL differential waveform emanating from C3/C4. Unlike Task A, Task B did not involve unsymmetric lateralized tactile distractors, which resulted in the absence of a significant CCP component following the onset of high-frequency vibration. Detailed statistical analysis for each component is furnished in the following subsections below.

Target-elicited Ppc (peak detection window: 50-200 after the lateral target onset. Note: middle visual distractor onset is 500 ms. Figure 4B Left panel**).** The Ppc component, indicative of early sensory processing, was anticipated across all conditions due to the target's lateral presentation. Paired samples t-tests established that the Ppc peak amplitude significantly exceeded the maximum of the baseline period (-200 to 0 ms) for all conditions (all ts < -4.233, all *p*s < .001).

A 2×5 repeated-measures ANOVA revealed a significant main effect for Distractor

Type ($F(4, 76) = 3.01$, $p = 0.023$, $\eta_p^2 = 0.137$) and a near-significant main effect for SOA ($F(1, 19) = 4.393$, $p = 0.05$, $\eta_p^2 = 0.188$). The interaction between SOA and Distractor Type was not significant ($F(4, 76) = 0.515$, $p = 0.725$, $\eta_p^2 = 0.026$). Post-hoc tests showed a significant larger Ppc peak amplitude when SOA is 150 ms (compared to 50 ms) (Mean Difference = 0.472, $p = 0.05$), whereas the Distractor Type comparisons did not yield significant differences when averaged across SOA (ps > .12).

Target-elicited N2pc (peak detection window: 150-300 after the lateral target onset. Fig 4B middle panel**).** The N2pc component plays a pivotal role in attentional allocation, and the extent of attentional engagement with targets is particularly influenced by the duration for which attention is exposed to distractors. We manipulated the SOA to investigate how allocating attentional resources to distractors versus targets evolves over time.

Paired sample t-tests confirmed that N2pc peak amplitudes were genuinely elevated in all conditions compared to the baseline period (-200 to 0 ms, ps < .001). A 2×5 repeated-measures ANOVA revealed a significant main effect of SOA ($F(1, 19) = 37.281$, $p < .001$, $\eta_p^2 = 0.662$). When the distractor and target were temporally proximal (SOA = 50ms), attention was predominantly captured by the distractor, leaving insufficient resources for allocation to the target. In contrast, when SOA was extended to 150 ms, attentional engagement with the target was enhanced, indicated by a significant increase in N2pc amplitude (Mean Difference = 1.113, $p < .001$). This suggests that a longer interval between the distractor and target enables a more pronounced engagement with the target.

Distractor Type also showed a significant main effect ($F(4, 76) = 14.964$, $p < .001$, $\eta_p^2 = 0.441$). Post hoc analyses indicated that TO and CM conditions elicited notably higher N2pc peak amplitudes compared to other visual distractors (ps < .006), while SF induced the lowest, except no significant difference was observed between SF and DCS ($p = .464$). However, there was no significant interaction between SOA and Distractor Type ($F(4, 76) = 0.463$, $p = 0.763$, $\eta_p^2 = 0.024$), which implies that the effects of distractor type on attentional engagement with the target were relatively consistent regardless of the SOA.

Target-elicited N2pc peak latency. The target-elicited N2pc latency refers to the onset of the lateral target. For instance, in the TO condition with an SOA of 50 ms, the peak latency is at 172 ms after the target onset. This peak latency is not indicated on the time values (x-axis) of the figure. When the SOA is 150 ms, the latency is 178 ms (i.e., 178 ms after the target onset). Similarly, in the SF condition, the peak latencies are 201 ms and 208 ms for SOA of 50 ms and 150 ms respectively (Figure 5 Right panel). A 2×5 repeated-measures ANOVA unveiled a significant main effect of Distractor Type, $F(4, 76) = 30.881$, $p < .001$, $\eta_p^2 = 0.619$. In contrast, the main effect of SOA was not significant, $F(1, 19) = 4.028$, $p = .059$, $\eta_p^2 = 0.175$. Additionally, the interaction between SOA and Distractor Type was not significant, $F(4, 76) = 0.28$, $p = .890$, $\eta_p^2 = 0.015$. Post hoc comparisons for Distractor Type revealed that TO and CM induced the shortest N2pc latency compared to all other distractor types. Specifically, both TO and CM showed significantly shorter N2pc latency than SF, DC, and DCS (differences > 19 ms, all *p*s < .001), with no significant difference between TO and CM ($p = .864$). SF showed longest N2pc latency but did not significantly differ from DC and DCS (*p*s > .060). The results indicate that the visual distractors (i.e., SF, DC, and DCS) slowed down N2pc latency compared to TO and CM conditions.

4.4 Discussion

The primary objective of the present study was to investigate the intricacies of attentional engagement and subsequent processing with respect to visual targets and distractors. A central aim was to explore how variations in distractor-target SOA and distractor-target similarity impact reaction times and neural correlates associated with attention. To accomplish this, we employed two distinct yet complementary tasks, Task A (Middle target/Lateral distractor) and Task B (Middle distractor/Lateral target), to systematically assess the effects of these parameters. Our behavioral findings revealed that distractors sharing more features with the target produced the most substantial interference. This aligns with the dimension and modality weighting accounts (DWA/MWA) positing down-weighting target-irrelevant features/dimensions/modalities when the target is fixed, resulting in minimal attentional allocation by distractors that do not share target dimensions (Liesefeld and Müller 2019; Zhang et al. 2019; Müller, Heller, and Ziegler 1995; Liesefeld, Liesefeld, and Müller 2022). Specifically, reaction times were generally faster when the SOA was lengthened. However, an intriguing exception was observed when the distractor had identical features to the target (SF condition). This reversed result can be ascribed to the robust attentional capture provoked by the distractor's similarity to the target.

A critical contribution of our study is the insight gained from analyzing event-related lateralizations (ERLs), focusing on the Ppc, N2pc, and P_D components. The N2pc component, indicative of lateralized attentional allocation, was notably influenced by both SOA and Distractor Type. Extended SOA (150 ms) was associated with intensified attentional engagement with the lateralized distractor (Task A), as evidenced by the amplified distractor-related N2pc amplitude. However, this did not coincide with the expected suppression pattern as indicated by the P_D component.

Notably, our findings challenge traditional interpretations of the P_D component as representative of distractor suppression. Instead, our results suggest a nuanced role for the P_D component. The consistent amplitude of the P_D component across various visual distractors (i.e., SF, DC, DCS conditions) at 150ms SOA implies that it might not exclusively reflect distractor suppression but could also signify a shift of attention away from the distractor (Kerzel and Burra 2020; Kerzel, Huynh Cong, and Burra 2021), particularly in conditions of extended distractor exposure. This novel observation posits that the P_D component could represent a more complex attentional process than previously understood. The following sections will expound on the implications of these findings.

It is inevitable to engage with the distractors containing target features because of top-down control

Our previous studies (Tsai et al., 2023a; Tsai et al., 2023b) applied similar target identification tasks as the current one, which led us to observe specific patterns in the Ppc components elicited by lateral visual stimuli (which could be both target or distractor). These components emerged around 100 ms after the onset of the lateral stimuli. Since the Ppc component is related to early sensory processing, it serves as an indicator of sensory registration preceding attentional engagement. If the stimulus aligns with the target's features, it will trigger attentional engagement. This can be observed as an N2pc that starts around 150 ms and peaks around 200 ms, which was the case in the SF and DC conditions in the current study. On the contrary, if the lateral stimulus lacks the target's features, we could detect the Ppc but not the N2pc. This observation was primarily seen in our previous studies, where the target and the distractor appeared simultaneously and were only present for 250 ms, after which the screen turned blank. This scenario, where the locations of the target and distractor were known in advance, resulted in the target being more likely to capture attention. This preferential attention towards the target may be why we did not observe any P_D component, traditionally an index of distractor suppression, in our previous studies.

For the current study, we employed the contingent attentional capture paradigm and manipulated the SOA between the distractor and target to be 50 ms and 150 ms. This approach was taken to observe the dynamic shift of attention between competing stimuli, without creating a resource competition scenario. More specifically, presenting the distractor earlier made it easier for the distractor to capture attention. The 50 ms SOA represents a period prior to the full registration of the distractor stimulus, creating a scenario where the target appears just as the distractor begins to be processed. This gives minimal time for distractor registration and prompts a rapid shift of attention from the distractor to the target. On the other hand, the 150 ms SOA represents a period following the distractor's sensory registration and the beginning of attentional engagement with the distractor. Having the opportunity to present the distractor earlier in the current study allowed for a detailed investigation of how attention dynamics respond when the target and distractor don't have to compete for cognitive resources simultaneously. Importantly, the chosen SOAs represent different phases of distractor processing, revealing distinct scenarios of attentional shift and suppression.

This research design opens up a critical discussion on the interplay between Distractor Type and SOA as it reveals the underlying dynamics of attentional engagement. According to goal-driven theories (Folk, Remington, and Johnston 1992; Leber and Egeth 2006; Becker, Folk, and Remington 2010), distractors sharing features with the target tend to capture attention more readily, resulting in prolonged reaction times and an elevated error rate. Our study reinforced this notion, particularly when the distractor was within the same dimension as the target, creating a robust interference. This interference can be attributed to the up-weighting of the target's dimension and features, which happens below the priority map, excluding spatial information (DWA, Found and Müller 1996; Liesefeld and Müller 2019). This resulted in the intra-dimension distractor being up-weighted, notwithstanding participants' awareness of the separate regions for the distractor and the target. In essence, region-specific shielding strategies could not be employed effectively.

According to the results from the crucial manipulation of SOA, generally, longer SOAs allow participants more time to prepare their response to the target, leading to faster reaction times. However, a noteworthy deviation from this trend was observed in the Same Features (SF) condition. Here, reaction times slowed down as SOA increased. This can be ascribed to the strong attentional engagement induced by the distractor's resemblance to the target. The extended SOA in this case might have allowed for a deeper processing of the distractor, making it harder to disengage and reorient attention towards the target. Contrastingly, in the Different Color and Same Shape (DCS) condition, reaction times were faster with longer SOAs, implying that the DCS distractor did not cause significant interference. This aligns with the general expectation that a longer SOA allows for more efficient preparation for responding to the target.

In Task A, where the target was specified in the middle line, the lateral intra-dimension distractor led to slower reaction times and a significantly larger distractor-induced N2pc amplitude than other types of distractors. This is indicative of attention being captured or engaged by the lateral distractor, necessitating additional time for reorientation to the middle target after disengaging from the lateral distractor. Conversely, in Task B, where the target was specified on the lateral side, the middle intra-dimension distractor captured participants' attention, resulting in relatively fewer attentional resources being allocated to the lateral target, as reflected by the smallest target-elicited N2pc amplitude compared to other distractor conditions.

Furthermore, the impact of location specificity on attentional engagement under the SF condition is worth highlighting. As per (Berggren and Eimer 2018; Sauter et al. 2018), the location shielding effect fails to eliminate the interference caused by distractors at known locations. This finding echoes our results where, despite participants being cognizant of the distractor's location, the SF distractor inevitably captured attention. This observation aligns with the Dimensional Weighting Account which posits that intra-dimensional distractors cannot be down-weighted.

An interesting aspect to consider is the role of the tactile vibration in the Target-Only (baseline) condition (Note: every trial initiated with the low-frequency (weak) tactile vibrations for all distractor types except the CM condition with high-frequency (strong) vibrations). Here, the absence of any visual distractor made the tactile vibration serve as an alerting signal. Notably, when the vibration was followed by a longer SOA of 150 ms (650 ms from the vibration starts to target onset), participants had more time to prepare, leading to faster reaction times to the target compared to an SOA of 50ms (550 ms from the vibration starts to target onset). This alerting role of tactile vibration could be a crucial factor contributing to the performance differences between conditions. The interplay between Distractor Type and SOA is pivotal in understanding attentional dynamics. The SF condition, in particular, unveils intriguing interactions, as the typical benefits of a longer SOA in preparing for target response are negated by the strong attentional engagement elicited by distractors resembling the target.

Differential impact of distractors with non-Target-features on reaction times as modulated by stimulus onset asynchrony (SOA)

Diving into the different-color (DC) condition first, where the distractor shares a shape feature with the target but has a different color. According to the Dimension Weighting Account, attention is more likely to be allocated to features congruent with the target, and the non-target color of the DC distractor would be down-weighted. However, it is crucial to recognize that the DC distractor still possessed the ability to capture attention due to the shape commonality with the target. This shape similarity accounts for the residual attentional capture observed in the DC condition, albeit diminished in comparison to the SF condition where both shape and color attributes align with the target.

Turning our attention to the DCS condition, wherein the distractor has both a different color and shape from the target, it was observed that longer SOAs led to faster RTs. This pattern, which is congruent with typical expectations (i.e., similar to the TO baseline condition), suggests that when the distractor does not share any features with the target, attentional resources can be allocated more efficiently to the target. Consequently, extended preparation time allowed by the longer SOA enhances performance.

These patterns underline the importance of the interaction between Distractor Type and SOA. Specifically, the SF condition demonstrates how similar features between the distractor and the target can lead to an unusual relationship between SOA and RTs, whereas the DC condition shows a relative immunity to SOA manipulation. Moreover, the DCS condition, which represents a distractor without any shared features with the target, aligns with conventional expectations regarding the role of SOA in response preparation. Supporting these behavioral observations, the N2pc amplitude, indicative of attentional engagement, aligns with the RT patterns. The DC condition, having a shared shape with the target, elicited a lower N2pc amplitude than the SF condition, highlighting reduced attentional engagement. The DCS condition, lacking any shared features with the target, further indicated that this distractor type was not substantially engaging attention (although the DCS distractor still captured attention and induced significant N2pc amplitude).

In summary, the dynamic interaction between Distractor Type and SOA not only reveals the intricate nature of attentional engagement, as reflected in the reaction times, but also highlights the role of neurophysiological indicators like the N2pc in this process. While the SF condition presents an atypical pattern with longer SOA durations leading to slower

RTs, it also elicits a stronger N2pc amplitude, indicative of increased attentional engagement due to shared features between the target and distractor. Conversely, the DC condition shows stability in RTs across SOAs and a lower N2pc amplitude due to the shared shape, but non-target color, of the distractor. This underscores a reduced attentional engagement. Finally, the DCS condition, lacking any shared features with the target, aligns with conventional expectations, exhibiting faster RTs at longer SOAs and lower N2pc amplitude, suggesting minimal attentional engagement. Thus, our findings underscore that both behavioral measures, such as RTs, and electrophysiological markers, such as N2pc amplitude, interactively demonstrate the complexity of attentional dynamics modulated by distractor type and SOA.

Rethinking the role of the P_D component in attentional dynamics

A striking finding is the intriguing behavior of the distractor-elicited P_D component as a function of SOA and Distractor Type. Traditional interpretations of the P_D component postulate its role primarily as an index of distractor suppression (Hickey, Di Lollo, and McDonald 2009; Sawaki and Luck 2010; Feldmann-Wüstefeld and Vogel 2019; Gaspar and McDonald 2014; Sawaki, Geng, and Luck 2012; Gaspelin and Luck 2018a; Burra and Kerzel 2013; Barras and Kerzel 2016, 2017). However, the patterns observed in our study contest this simplistic narrative and insinuate a more convoluted role. When SOA was 50ms, the P_D component displays a gradient in amplitude with respect to the distractor-target similarity: The SF condition that the distractor shared target features most elicited the largest P_D, followed by DC, and with DCS yielding the smallest. Remarkably, this hierarchical structure mirrors that of the distractor-N2pc component, where its amplitude decreased as the target-distractor dissimilarity increased. This opposite patterns (see Figure 4) suggest a close interdependence between attentional capture and subsequent reactive suppression and disengagement mechanisms when the target and distractor were still in the competitive mode.

The patterns changed when the distractor-target SOA increased to 150 ms. The amplitude of distractor-N2pc continued to increase, following a similar trend as the 50 ms SOA (Figure 4). However, the P_D amplitude no longer decreased as the distractor-target dissimilar increased. Instead, the P_D amplitude remained consistent across the SF, DC, and DCS conditions (at around 4.3 uV). This leveling-off pattern cannot be easily explained within the traditional interpretation of P_D as merely reflecting reactive suppression (e.g., Liesefeld, Liesefeld, and Müller 2022; Tsai et al. 2018; Liesefeld et al. 2017;

Feldmann-Wüstefeld, Weinberger, and Awh 2021; van Moorselaar and Slagter 2019), especially considering the varying degrees of attentional capture observed in the N2pc amplitude across the three distractor conditions. Were that the case, one would expect P_D amplitudes to follow the similar pattern observed at the shorter SOA, with SF eliciting the most substantial P_D due to its greater attentional capturing ability.

One plausible interpretation of these results is that the P_D component may not only represent reactive suppression but also indicate the degree of disengagement. At the 150 ms distractor-target SOA, the prolonged exposure to the distractor could lead to full attentional disengagement for all three distractor conditions (SF, DC and DCS), resulting in similar P_D amplitudes. On the other hand, for the shorter 50 ms SOA, proactive suppression was at play for the DC and DCS conditions, resulting in incomplete distractor engagement, and thus requiring less disengagement.

In short, our findings prompt a reevaluation of the role of the P_D component in attentional dynamics. The classical interpretation of P_D as an indicator of distractor suppression is challenged, and a more comprehensive representation involving attentional shifts is suggested. At least, the P_D component may reflect reactive suppression and disengagement processes.

Examining the role of cross-modal tactile vibrations in alerting and visual search performance

In our investigation, we added a novel element by incorporating a Cross-Modality (CM) condition, in which high-frequency tactile vibrations were used as alerting cues. Contrary to their traditional role as distractors in our previous work (e.g., Tsai et al., 2023a; 2023b), these tactile vibrations were designed to precede the visual target presentation, preparing participants for the forthcoming visual search task. The timing of the tactile vibrations, occurring either 550 ms or 650 ms before the target presentation, was an important aspect of this study. These vibrations, characterized as 'deviant conditions' and making up only 20% of the task trials, were hypothesized to stimulate the attentional system, priming participants to the upcoming visual target.

Critically, we employed the Contralateral Central Negativity (CCN) as a measure to gauge the sensation of these tactile stimuli. The CCN served as evidence of tactile sensory registration (Forster, Tziraki, and Jones 2016; Martin Eimer et al. 2004; M. Eimer and Driver 2000; Töllner et al. 2009; Nasemann et al. 2023; Tsai et al. 2023), indicating that participants were indeed processing the high-frequency vibrations. This is consistent with our previous studies (Tsai et al., 2023a; 2023b), which showed neural processing of tactile information.

However, the results of our study did not indicate a significant improvement in performance in the CM condition relative to the baseline. This suggests that despite the sensory registration of the tactile stimuli, these cross-modal cues did not effectively engender a priming or alerting effect potent enough to modulate visual indentification performance. This could be due to the down-weighting of the tactile modality, as per the Modality Weighting Account (Nasemann et al. 2023; Töllner et al. 2009), or possibly, the alerting cues were not robust enough in the given context. In conclusion, our findings align with the MWA theory, which proposes that the tactile vibration, as a cross-modal stimulus, is down-weighted and does not result in performance enhancement.

Conclusion

This study sheds light on critical aspects of attentional control by the manipulation of stimulus onset asynchrony (SOA). Particularly, we propose an alternative interpretation of the P_D component, suggesting that it signifies disengaging attention from distractors rather than the degree of reactive suppression. This re-conceptualization offers a more sophisticated perspective on the role of P_D in attentional regulation. Furthermore, our findings indicate that when distractors possess a higher number of target features, attentional capture amplifies, as evidenced by the distractor-N2pc component - a recognized indicator of attentional deployment. This observation underscores the selectiveness of attention contingent on stimulus characteristics.

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Chapter 5: General Discussion

General Discussion

The primary purpose of this thesis is to examine how we deal with distractors, with a particular focus on proactive and reactive suppression mechanisms. To control attention, proactive and reactive strategies can coexist and work together. In Study 1 (Chapter 2) and Study 2 (Chapter 3), when distractor and target simultaneously appeared, we observed a clear role for proactive suppression. Using the framework of the Dimensional Weighting Account (DWA, Found and Müller 1996; Müller, Heller, and Ziegler 1995; Liesefeld and Müller 2019; Müller, Reimann, and Krummenacher 2003), these studies showed that proactive suppression is an effective strategy when we can predict and prioritize critical information, and reduce interference from distractors. However, Study 3 (Chapter 4) introduced a different approach by presenting the distractor before the target, making it more attention-grabbing. In this scenario, proactive suppression alone wasn't enough to avoid the distractor's interference. This is where reactive suppression comes into play, redirecting attention away from the distractors. In the following sections, we will explore deeper into the findings of Studies 1-3 and discuss how these two suppression strategies work in different scenarios, linking our results with existing research.

In Study 1, we systematically manipulated the definition of additional singleton distractors in a task requiring (present/absent) detection of a fixed odd-one-out target shape, presented in displays with collocated visual and vibro-tactile items. The target was invariably a (blue) square among (blue) circles, while the additional singleton distractor could be either another odd-one-out shape (intra-dimension distractor: blue triangle), an odd-one-out color (cross-dimension distractor: magenta circle), or an odd-one-out vibro-tactile stimulus (cross-modal distractor). The target and the various types of distractor were equated in terms of the respective (shape, color, and vibro-tactile) feature contrasts, making them equally competitive for bottom-up attentional capture. We found that, behaviorally, the intra-dimension (Shape) distractor interfered substantially with target detection, manifested by slowed responses on both target-present and, in particular, target-absent trials and larger error rates (misses on target-present trials and, in particular, false alarms on target-absent trials). In contrast, cross-dimension (Color) distractors caused hardly any interference at all, while cross-modal (Vibro-tactile) distractors generated some interference (on target-absent trials). Electrophysiologically, this pattern was mirrored in the N2pc and CDA components: the target-referenced N2pc and CDA amplitudes were reduced in the presence of an intra-dimension distractor as compared to both cross-dimension and cross-modal distractors, with the latter also exhibiting some numerical reduction of the N2pc amplitude; compared to the target-only condition, the N2pc (and CDA) amplitude was undiminished in the presence of a cross-dimension distractor.

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, as well as a marked cCDA. The larger cCDA amplitude in the DO-Shape (target-absent) condition relative to the other distractor-only conditions might reflect processes of response inhibition: the shape distractor may have evoked an erroneous 'shape-target-present' response, which participants had to inhibit and issue the alternative ('target-absent') response. This would be consistent with a recent study on inhibitory control of error correction (Rodríguez-Herreros et al. 2021). In this study, participants had to respond to the target's pointing direction, while the target pointed to, say, the right in the very beginning of a trial, but then, after 200 ms, changed to point to the left, with the correct response being 'left'. Rodríguez-Herreros et al. (2021) observed the LRP (similar to the cCDA in the present study) to be enhanced for correct responses on such target-switch trials. The cross-dimension distractor induced no N2pc; and the vibro-tactile distractor elicited a robust CCN, though only a numerical N2pc. Of note, none of the three distractor types was found to elicit a significant P_D.

In Study 2 and Study 3, we adopted an alternative approach to understand the mechanisms of attentional control by utilizing a variant of Eriksen's flanker task (Eriksen & Eriksen, 1974). In the classical flanker task, participants are required to respond to a central target while ignoring neighboring distractors. Response times are typically longer in incongruent conditions (e.g., responding to the direction of the central arrow in "> > < > >") compared to congruent (e.g., "> > > > >") and neutral conditions. Due to the fixed target location in the flanker task, participants may employ spatial shielding strategies to filter out signals from the distractor locations. In our studies, the same-feature distractor (a blue triangle identical to the target but always oriented in the opposite direction) was specifically designed to induce flanker conflict effects, thereby slowing reaction times. Unlike the traditional additional singleton task, our aim was to further understand the dynamics of spatial selection by investigating how spatial (Study 2 and Study 3) and temporal (Study 3) factors influence performance. Through this design, we could particularly assess participants' attentional engagement with same-feature distractors using ERL components.

Study 2 and Study 3 build upon the foundation established by Study 1. We executed cross-modal target identification tasks (response to the blue triangle's orientation) with EEG recordings to examine pivotal ERL components: Ppc, N2pc, P_D, and CCN. Importantly, the target was defined by a specific visual shape and color, positioned either centrally or laterally (i.e., Task A: middle target, lateral distractor; Task B middle distractor, lateral target). Distractors were diversified into within-dimension (matching the target), cross-dimension (differing in color/shape from the target), or cross-modality (tactile vibrations). The main difference in experimental design between Study 2 and Study 3 is the manipulation of SOA between distractor and target. In Study 3, we introduced distractors 50 to 150 ms prior to the target. Both Study 2 and Study 3 observed that the within-dimension distractor notably prolonged reaction times. Cross-dimensional distractors brought about minimal interference, whereas cross-modality distractors had no effect on performance. Distractors containing more target features captured more attention, as shown by the N2pc, thus enhancing attentional engagement. In Study 3, the subsequent P_D highlighted attentional disengagement from the distractor. But there was no significant P_D component observed in Study 1 and Study 2. This suggests that the proactive suppression was more successful (this part will be discussed in the following section). While the tactile distractor captured attention, as evident from the CCN, it did not reduce the attentional deployment to the visual target. Results from Studies 2 and 3 align with Study 1 and suggest the distractor with target-relevant features deteriorated performance because of top-down attentional engagement.

Overall, this pattern of results is in accord with the dimension- and modality-weighting accounts proposed by Müller and, respectively, Töllner and colleagues (Müller, Heller, and Ziegler 1995; Found and Müller 1996; Liesefeld and Müller 2019; Töllner et al. 2009b). The intra-dimension (Shape) distractor is handled least efficiently because the distractor-defining dimension (Shape) cannot be selectively down-weighted without impacting the processing of a target defined in the same dimension; in contrast, down-weighting is feasible, and in fact, near-perfect, when the distractor is defined in another visual (the Color) dimension (cross-dimension distractor). The same applies to a distractor defined in another (the Vibro-tactile) modality (cross-modal distractor). The vibro-tactile distractor did cause some interference (on target-absent trials), though possibly because the task required search for a *visual* target and vibro-tactile distractors were relatively rare compared to visual distractors.

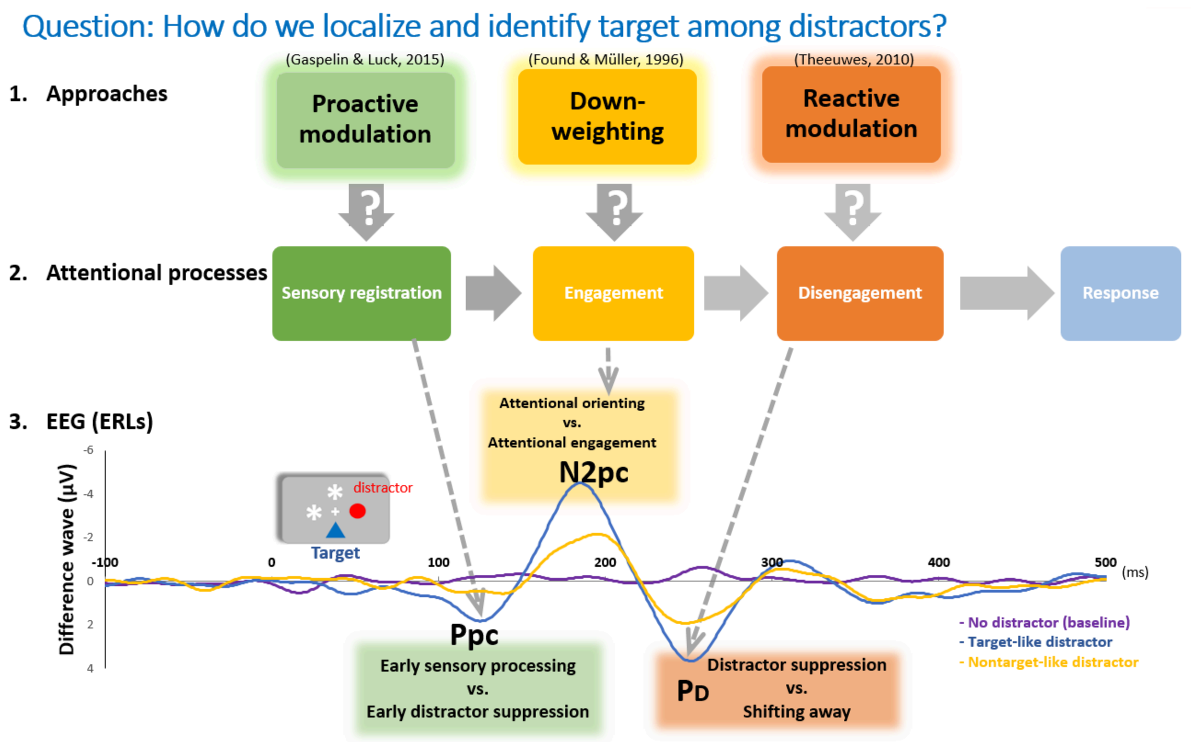

Figure 1. Framework depicting attentional processes and associated ERP components during visual search. The figure summarizes the main findings of this thesis and delineates the attentional processes along with their corresponding ERP (ERL) components. It illustrates three distinct approaches to distractor handling: proactive modulation, down-weighting, and reactive modulation. The key attentional stages are linked to specific ERP markers: (1) Sensory registration is signaled by the Ppc component, denoting initial attentional capture by a salient distractor (this figure shows the example that a lateral red distractor elicits the ERL components). (2) Engagement, marked by the N2pc component, reflects the allocation of attentional resources on the distractor, modulated by proactive down-weighting strategies from the DWA/MWA frameworks. (3) Disengagement is reflected by the P_D component, which suggests a shift of attention away from the distractor rather than mere suppression. This stage is characterized by reactive modulation. (4) The final stage, Response to the target, involves executing a targeted motor action. This structured framework enhances the comprehension of attentional control mechanisms during a search task.

5.1 Dimension/modality-based distractor handling

In the three studies, the target-defining feature (i.e., a blue Square shape in Study 1; a blue triangle in Study 2 and Study 3) was known in advance. So, in principle, participants could use a feature-template-based strategy (Duncan and Humphreys 1992; Folk, Remington, and Johnston 1992; Wolfe and Horowitz 2004) to top-down bias search towards the task-relevant feature (blue) 'square' (the example in Study 1). 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 different types of distractor. In theory, this would also have been the 'optimal' strategy, given that the target never changed while the distractor was variable across trials. Yet, we found that target detection search was strongly interfered with by the presence of an intra-dimension distractor, but not (or only marginally) by the presence of a cross-dimension or a cross-modal distractor. This pattern is indicative of other mechanisms, in addition to or instead of a top-down feature-based set, having been at play to determine distractor handling, in particular: dimension- and modality-based mechanisms. According to the dimension-weighting account (DWA, Found and Müller 1996; Liesefeld and Müller 2019), at least in saliency-driven search tasks, it is not possible to set oneself for, or selectively 'up-weight', a specific target-defining feature (e.g., Square in Study 1) without setting oneself for, or 'up-weighting', the encompassing feature dimension (in the example, Shape/Form). Accordingly, any feature-contrast within the target-defining dimension would be up-weighted in the computation of attentional priority – which is why a distractor singleton defined in the same dimension as the target (such as a Triangle in Study 1) is a strong competitor for the allocation of attention. Further, according to the DWA, the up-weighting of one (task-relevant) dimension goes along with the down-weighting of other (irrelevant) dimensions – 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 attention. The modality-weighting account (MWA, Töllner et al. 2009a) provides a simple extension of this notion to multi-modal search scenarios, by assuming an additional 'modality' layer (above a 'dimension' layer) in priority computation: if the searched-for target is defined in one particular modality, all dimensions (and features) in this modality are up-weighted, and irrelevant modalities are down-weighted. Accordingly, when search is set for a visual target, distractors singled out in a non-target-defining modality (such as a vibro-tactile stimulus) are non-competitive for attention. Thus, overall, the DWA and MWA provide a relatively consistent account of the behavioral effects in the three studies in this thesis. Recall, though, that – in contrast to the cross-dimension distractor – the vibro-tactile distractor appeared to produce some interference (especially on target-absent trials), which would not be predicted by a strict version of the MWA; we will return to this issue below (see Section *Cross-modal distractor handling*).

One critical prediction of the DWA/MWA is that dimension/modality-based distractor suppression works only with cross-dimension/modal distractors, but not intra-dimension distractors (Liesefeld and Müller 2019; Zhang et al. 2019; Müller, Heller, and Ziegler 1995) – a pattern confirmed by the 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 (in all three studies), but significantly reduced amplitude when an intra-dimension (Shape-defined) distractor competed with the target for the allocation of attention (i.e., the TD-shape condition in Study 1; the same-feature distractor condition in Study 2 and 3). Given that the target and distractor appeared on opposite sides of the display in Study 1, this suggests that attention was (near-equally) equally distributed to the target and distractor. This interpretation was further supported by Study 2 and 3, in which we analyzed both the target-elicited N2pc (with the middle distractor in Task B) and the distractor-elicited N2pc (with the middle target in Task A). The two complementary tasks showed that the intra-dimension distractor summoned attentional resources diminishing the resources available for processing the target. In contrast, the target-elicited N2pc was (nearly) undiminished when a cross-dimension or cross-modal distractor (TD-color and TD-vibration conditions in Study 1; DCS and CM conditions in Study 2 and 3) – indicating that such distractors did not compete for the allocation of attention. Consistent with this, only the Shape distractor elicited a robust N2pc (i.e., DO-Shape condition in Study 1; SF condition in Studies 2 and 3), but not the Color distractor or the Vibration distractor.

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 working memory, that is, of the working-memory resources demanded, or ‘engaged’, by selected items to accomplish the task at hand (Chen et al. 2022; Zinchenko et al. 2020; Töllner, Mink, and Müller 2015; Töllner et al. 2014; Wiegand et al. 2014). As indicated by the N2pc effects, the intra-dimensional distractor attracted attention. That is, in the TD-Shape condition in Study1 and the same-feature distractor (SF) in Study 2, it was selected along with the target (evidenced by the near-zero target-elicited N2pc amplitude), drawing away processing resources from the target at the post-selective stage – the latter being reflected in the target-related CDA being reduced in the TD-Shape/SF compared to the target-only (TO) condition. In contrast, the CDA was undiminished, compared to the TO baseline, in the Color and Vibration conditions, indicative of full post-selective processing of the shape target in the presence of color- and, respectively, vibration-defined distractors – because distractors of the latter types were not attentionally selected (evidenced by the undiminished target-elicited N2pc's in these conditions). This pattern of CDA effects was seen both for electrode pair PO7/PO8 and pair C3/C4 (where we refer to the latter CDA component as cCDA).

This pattern of behavioral and electrophysiological results is generally in line with the DWA/MWA, where the N2pc effects are best explained in terms of an attentional engagement account. In the next section, we discuss how the results fit with the 'signal suppression' (2018a; Gaspelin, Leonard, and Luck 2015; Gaspelin and Luck 2018c) and the 'attentional capture, rapid disengagement' (Theeuwes 2021, 2010) accounts.

5.2 Implications for the 'attentional capture, rapid disengagement' and 'signal suppression' accounts

Our findings cannot be easily squared with the idea that the distractors invariably captured attention and control was then exercised reactively, by rapid disengagement of attention from the distractor and re-orientation to the target (Theeuwes 2021, 2010). Of note, however, our distractors were equally (bottom-up) salient to the target, rather than more salient. Accordingly, one would not have expected the distractors to capture attention on all trials; rather, according to the 'probabilistic capture' model of Zehetleitner et al. (2013), the predicted capture rate would only be nearing 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; Theeuwes 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, making participants adopt a pure 'singleton detection' search mode (cf. Bacon and Egeth 1994; Chang and Egeth 2019; Gaspelin, Leonard, and Luck 2015; Gaspelin and Luck 2018a). In the present studies, by contrast, the target shape (and color) were completely predictable, as were the distractor features – in principle allowing participants to top-down bias search towards the critical target feature by setting up a positive (square-shape in Study 1; triangle-shape in Study 2 and 3) target template, as well as against distractor features by setting up negative (triangle-shape in Study1/ circle-shape in

Study 2, red-color, and 100-frequency vibration) distractor templates. That is, by permitting search to be feature-driven[17], the present conditions may have been non-optimal to test a strong 'attentional capture, rapid disengagement' account. Nevertheless, this account would find it hard to explain why only the intra-dimension (shape) distractor caused significant behavioral interference (relative to the target-only baseline) – based on the electrophysiological evidence attributable to attentional engagement – but not the color and vibro-tactile distractors, even though the distractors were equated for bottom-up salience. Further, even when the intra-dimension (shape) distractor drew attentional resources, we found no electrophysiological evidence of a re-active suppression process, in particular: while the intra-dimension (shape) distractor generated an N2pc (Note: In Study 1, as can be inferred from the near-absence of a target-elicited N2pc on trials with a intra-dimension (shape) distractor on the opposite side [TD-Shape trials]; the distractor-generated N2pc can be seen in undiminished form on DO-Shape trials. In Study 2, during the complementary tasks, the sum of distractor-elicited N2pc and target-elicited N2pc in the same-feature distractor condition was analogous to the target-elicited N2pc observed in the target-only condition.), 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). Instead, the Shape distractor appeared to be processed in parallel with the target at the post-selective stage (Study 1 and 2, but not Study 3), that is, both were represented in working memory and perhaps compared to the target template (as evidenced by the reduced target-elicited CDA on TD-Shape trials).[18] 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 (2018a; Gaspelin, Leonard, and Luck 2015; Gaspelin and Luck 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

[17] Although a feature-based search mode was possible in principle, the fact that participants failed to keep the Shape distractor out of search guidance 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 and Egeth 1994; Chang and Egeth 2019; Gaspelin, Leonard, and Luck 2015; Gaspelin and Luck 2018a) – this mode was not effective in dealing with intra-dimension distractors (even though the distractor and target were separable by basic, orthogonal vs. oblique, edge orientation features).

[18] Possibly, the lack of a post-capture Pd may be owing to the limited, 200-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 (Martin Eimer and Grubert 2014).

vibro-tactile 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 (in Study 1), even though triangles are separable from squares based on possessing unique (oblique) side orientations (Buetti, Xu, and Lleras 2019; Xu, Lleras, and Buetti 2021; Grüner, Goller, and Ansorge 2021; Wolfe and Horowitz 2004, 2017). 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, at least dimensionally) fixed distractor type, rather than, as the three studies, randomizing the distractor types across trials – and perhaps there is a 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 tasks. 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 (or, in fact, any) P_D component in Study 1 and Study 2 (the P_D in Study 3 will be discussed in the next section), that is: successful pro-active distractor suppression was not associated with an ERP signature assumed, by the signal-suppression hypothesis, to reflect the active prevention of attention (mis-)allocation to the distractor. This can be taken to indicate that no P_D, or process reflected in the P_D, is strictly necessary for successful pro-active distractor handling.

This is consistent with the DWA/MWA, which explains *pro-active* distractor suppression in terms of the down-weighting of feature contrast signals in task-irrelevant dimensions/modalities. As the weight settings (tonically) 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). As a result, they are not passed, or passed only in weakened form, 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.

A different notion of proactive suppression appears to be implied in the 'signal-suppression' hypothesis. According to this account, distractors generate an 'attend-to-me' signal on the priority map, 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 (early) Pd, permitting the target to be selected without, or only little, interference. 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 registration of the distractor signal (at a level where it can influence attention-allocation decisions) in the first instance.

Thus, it remains that distractor suppression sometimes involves processes reflected in a P_D (e.g., Gaspelin and Luck 2018c; Steven J. Luck et al. 2021), and sometimes processes that do not involve a P_D (e.g., Gaspar and McDonald 2014; Study 1 and 2). Given this, further work is needed to delineate the conditions under which distractor suppression works in one or the other mode. As alluded to above, one potential factor may be the number of different distractor types that may be (unpredictably) encountered on a given trial. If there is only one, featurally fixed type of distractor, it may be feasible to set up a distractor template so as to actively suppress this type of stimulus.[19] However, template-based suppression may be too demanding of working memory resources when there are too many different distractor types (from different dimensions/modalities) and multiple distractor templates would need to be maintained – in which case participants may switch to a cognitively less demanding, dimension/modality-weighting strategy. 'Learning' may be another factor determining which strategy is applied. While observers may initially adopt a 'laborious' template-based strategy (requiring cognitive control), with practice they may 'discover' that a dimension/modality-weighting strategy is more easier to operate (see, e.g., Müller et al., (2009) and Zhang et al., (2022), who showed that, with sufficient practice, participants tend to develop a dimension-based strategy under conditions of random color swapping).

[19] Conceivably, such a template-based suppression may also work in scenarios with featurally variable distractors defined in a fixed non-target dimension, such as variable color distractors in search for a shape-defined target – in which case the distractor template could specify suppression of any, say, 'not blue' stimulus when the target is known to be invariably blue. However, evidence suggests that people do not use such Boolean 'not' operators (e.g., Joseph Krummenacher, Grubert, and Müller 2010), and in any case they would fail under conditions of random color swapping.

5.3 Cross-modal distractor handling

Interestingly, while the vibro-tactile distractor could be kept as well out of search as the color distractor, its presence gave rise to slower responses relative to the color distractor on target-absent trials. In other words, unlike the cross-dimension distractor, the cross-modal distractor gave rise to some interference, but only when it was the only salient item in the display and not when it faced the competition of the task-relevant Shape item. The fact that the cross-modal distractor could not be completely disregarded (at least on target-absent trials) would appear to provide a challenge to the MWA (Töllner et al. 2009a). This account (which was devised to account for the costs associated with shifts of the target modality across trials) assumes an additional 'modality' layer between the (intra-modal) 'dimension' layer and the overall priority map, with modality weights assigned according to the task relevance (and inter-trial history) of the various stimulus dimensions. In the present search scenario, the tactile modality was never task-relevant, and so, according to the MWA, its assigned selection weight should have been less than that assigned to visual modality (as the target was invariably defined in the latter modality). Consequently, the MWA would have predicted the cross-modal distractor to cause less interference than the cross-dimension distractor – but it turned out that it interfered more.

Electrophysiologically, the vibro-tactile distractor elicited a strong early CCN/CCP component in the sensorimotor region (C3/C4) on both target-present and -absent trials (recall that the CCN is reversed to CCP, because, in the target-absent conditions, the reference is the distractor, rather than the target, location), indicative of the registration of the tactile singleton by the system on both types of trial. However, in the presence of a competing target, the tactile distractor did not give rise to a significant N2pc difference in the parietal-occipital region (PO7/PO8) relative to the target-only condition (just like the color distractor), despite the early significant CCP component in the sensorimoter region. The fact that the CCP did not affect the target-elicited N2pc component would suggest that the CCP component is most likely a representation of an odd-one-out touch sensation in the sensorimotor region, rather than the engagement of limited attentional resources (diminishing the resources available to process the visual target). In other words, the tactile distractor was spatially registered as a stimulus competing with the target, though without engaging attention. However, on target-absent trials, the absence of a target would have led to uncertainty as to the required (target-present/absent) response and, as a result, re-checking whether a target signal may have been overlooked. In this re-checking phase (the standard explanation of the slower RTs on target-absent vs. -present trials), the distractor signal may have engaged attention and been 'inspected' on some trials to rule out that it was generated by a target. This could explain why an interference effect by the cross-modal distractor arose only on target-absent trials. In principle, the same should have happened with a color distractor. However, recall that tactile distractors were less likely than visual distractors, conferring tactile odd-one-out signals a relatively higher 'surprise' value and thus greater interference potential when they occurred.

Exactly how this fits with the MWA would need to be examined in future work. As it stands, the MWA is just a general schematic account which is insufficiently developed to specify the underlying neural dynamics.

5.4 Proactive vs. reactive suppression

Our studies aim to know if the role of distractor handling is proactive or reactive. The aforementioned results from Studies 1 and 2 focus more on proactive suppression (Geng 2014; van Moorselaar and Slagter 2020; Theeuwes, Bogaerts, and van Moorselaar 2022) and are in line with the DWA/MWA. In this section, we will discuss more about reactive suppression based on the findings from Study 3 of this thesis. Moreover, it is crucial to point out the meaning of the controversial P_D component, traditionally viewed as the index of distractor suppression. By delving deep into the dynamics of attentional engagement and its modulation by Stimulus Onset Asynchrony (SOA) and Distractor Type, a multifaceted story of suppression emerges, challenging established paradigms.

Study 3 delved deep into how the dynamics of attention are impacted when confronted with various distractor types (i.e., SF, DC, and DCS) and varying SOA. An essential aspect brought to light was when a distractor was presented alone, leading to participants being more easily drawn to it, thus undermining the efficacy of proactive suppression. This phenomenon underscores the need for reactive suppression even in the presence of proactive strategies. Most crucially, our findings challenge the traditional understanding of the P_D component. While P_D has traditionally been seen as a marker for distractor suppression, our results suggest it may instead represent the act of disengagement or reorientation from the distractor. This re-interpretation emphasizes the notion that attention dynamics, especially in contexts where distractors are particularly salient and proactive suppression falls short, involves not just suppression but, more importantly, the ability to disengage and reorient attention.

Traditionally, the P_D component has been viewed as an index of distractor suppression. However, there are three different kinds of P_D: (1) early P_D without N2pc (e.g., Forschack, et al., 2023; Gaspelin & Luck, 2018; Gaspar & McDonald, 2014), (2) N2pc preceding the P_D (e.g., Tsai et al., 2023c; Liesefeld et al., 2021; van Moorselaar & Slagter, 2019a), and (3) P_D before N2pc (e.g., Kerzel and Cong, 2023; Kerzel and Burra 2020; Sawaki et al., 2012). The first type of P_D appears earlier and aligns with the signal suppression theory that the P_D is the active suppression to avoid attentional capture by the distractor. Because of this active suppression, we do not see any N2pc following the early P_D. However, Study 3 in this thesis revealed the second type of P_D - N2pc preceding the P_D. In other words, the P_D in this case is more related to reactive suppression. Although we would say this P_D is about disengagement rather than suppression, we will discuss this in the following section. The third type of P_D also shows patterns of attentional re-direction or deploying attention to the opposite location of the salient distractor.

In the context of a 50 ms SOA, Study 3 reveals a gradient in P_D amplitude, reflecting the similarity between distractors and targets. Interestingly, the trend mirrors that of the distractor-N2pc component. Such findings intimate a finely-tuned interplay between attentional capture and subsequent disengagement mechanisms when stimuli compete. Yet, as SOA extends to 150 ms, P_D no longer offers a linear representation of distractor-target dissimilarity. Instead, its amplitude plateaus, suggesting that traditional notions of P_D solely representing suppression might be overly simplistic. While there might be concerns about the P_D amplitude reaching a ceiling effect, the fact that its absolute values do not exceed those of the N2pc suggests that such concerns are unwarranted. It seems that the P_D amplitude does not increase as the need for more suppression grows.

The paradigm shifts further when comparing the effects of shorter (50ms) and longer (150ms) SOAs on suppression mechanisms. In the 50ms SOA scenario, the different color distractor (DC) and different color/shape distractor (DCS) conditions demonstrate proactive suppression – the brain suppresses attentional engagement even before complete distractor processing. The smaller distractor-elicited N2pc in the DCS condition indicates that proactive suppression works better in the DCS than in the DC condition. The differential P_D amplitudes might then indicate varying degrees of initial engagement, leading to consequent reactive suppression needs. Conversely, in the context of a 150ms SOA, the consistent P_D amplitude across conditions suggests that, after prolonged distractor exposure, full attentional disengagement is achieved irrespective of the distractor type. Such patterns hint at a reactive nature of suppression, where the brain reacts to attentional capture by uniformly disengaging attention from all distractors. This unified response contrasts starkly with the nuanced reactions seen at shorter SOAs. Similar to a recent study, Forschack et al. (2023)observed both salient and less salient distractors elicited Pd components of equal amplitude, suggesting that the Pd component does not reflect proactive distractor suppression. It seems that the P_D is for shifting away from the distractor and reorienting to the target, and this process is less related to the efforts of engaging with the different types of distractor.

Combining these observations, we propose a hybrid account where the P_D component reflects attentional disengagement, which combines shifting away from the distractor and some suppression processes. Although we do not precisely know how much of the P_D is for shifting away and for suppression, our exploration in Study 3 accentuates the need for a more comprehensive appreciation of attentional dynamics. Bridging the delicate balance between proactive and reactive suppression offers a fresh perspective on how the brain optimally juggles attentional demands amidst competing stimuli. As such, this finding invites future research to further dissect these complex processes, fostering a deeper understanding of the intricacies of human cognition.

5.5 Outlook for Future Studies

The results from Studies 1-3 give us a better understanding of how distractor suppression works. As we move forward, there are several research directions to explore:

(1) Temporal Dynamics:

Future research should systematically investigate the temporal dynamics of distractor suppression, with a specific emphasis on the interval between distractor and target presentations. The latency of distractor onset may critically modulate both proactive and reactive suppression mechanisms. A careful examination of the time course of N2pc and P_D, markers of attentional engagement and disengagement, is essential. Although Study 3 presented an alternative interpretation of P_D as indicative of attentional diversion from distractors rather than pure suppression, further evidence is essential. An experimental paradigm akin to that utilized in Study 3, but with varied stimulus onset asynchronies (SOAs), may shed light on this. Specifically, the following three examples like (1) employing SOAs of [50, 200, or 450 ms (in this case, the distractor would appear earlier than the target)], (2) SOAs of [-150 (the negative SOA means the target will appear first), -50, or 50 ms], and (3) SOAs of [-100 (target appears first), 0 (target and distractor present concurrently), or 100 (distractor appears first) ms] would provide insight into the impact of distractors and their timing on attentional control. The above SOAs are considered to be the timing of Ppc (around 100 ms after the lateral stimulus onset), N2pc (around 200 ms after the lateral stimulus onset), and Pd (around 300 ms after the lateral stimulus onset).

(2) Neural Correlates and Causal Evidence in Distractor Suppression:

The neural mechanisms involved in proactive and reactive suppression are still being explored. Combining fMRI with transcranial magnetic stimulation (TMS) can provide a more comprehensive understanding of the brain regions involved in these processes. Preliminary insights from Zhang et al. (2022) demonstrate the pivotal role of the early visual cortex in modulating neural excitability in response to distractors. This suggests that proactive suppression, contingent on learning, predominantly modulates early visual areas instead of higher-order cortices, such as the frontal regions. Exploring causal mechanisms may benefit from the application of TMS (or tDCS, tACS) experiments. For instance, theta burst stimulation applied to early visual areas (e.g., V1) versus regions like FEF and rPFC could provide clear evidence of the critical brain regions for proactive suppression. Similarly, we can apply the same strategy to reveal the reactive suppression mechanism.

The other approach to testing the neural mechanisms of distractor handling should combine TMS and EEG. Based on our Studies 1-3 and previous research, the functions of specific ERL components such as N2pc and P_D are well established. We can conduct TMS-EEG experiments informed by fMRI findings to stimulate specific regions for either proactive or reactive suppression and observe the effects represented by ERP indices. For example, if the rIFG is linked to inhibitory control, TMS modulation on the rIFG might result in a smaller P_D amplitude in distractor conditions, suggesting a deficiency in reactive suppression abilities.

(3) Task Considerations in Studies of Distractor Handling:

The choice of experimental paradigms significantly affects the study of suppression mechanisms. The additional singleton paradigm is valuable but has limitations due to factors like set size (e.g., eight items vs. four items) and stimulus homogeneity versus heterogeneity. Even the presence of placeholders before target or distractor onset plays an important role. For example, Forschack et al. (2022) noted that P_D amplitude decreases in the absence of location fillers.

To broaden our understanding, it's important to explore alternatives like the Rapid Serial Visual Presentation (RSVP) task or other paradigms. Controlling for confounding factors, such as working memory load, is crucial. Different set sizes can influence how suppression mechanisms manifest. Additionally, real-world examples of distraction, like writing a manuscript with a vibrating phone or finding a friend in a busy station, can provide practical insights. Examining how findings from controlled lab experiments apply to real-world situations can make our research more relevant.

(4) Clinical Implications:

Research into distractor suppression may open new avenues for clinical applications, particularly for populations with attention deficits. While ADHD is a well-known example, other conditions such as depression and anxiety also involve significant attentional problems. For instance, individuals with depression often struggle with rumination, a repetitive thinking pattern linked to poor attentional control.

Currently, psychiatric diagnoses heavily depend on doctors' conversations with patients, which can lead to a high risk of misdiagnosis, especially in conditions like anxiety and depression. These methods lack the objective precision that neurophysiological markers can provide. The attention tasks developed in our research, which highlight proactive and reactive suppression dynamics, hold promise for becoming direct, efficient diagnostic tools. These tools might significantly enhance psychiatric diagnosis by offering physiological evidence to reduce misdiagnosis rates. Furthermore, they could serve as sensitive indicators of cognitive changes throughout the lifespan, aiding in aging research, such as cognitive decline or dementia, and understanding related neural changes.

5.6 Conclusion

The studies in this thesis provide insights into the neural mechanisms of attentional control and distractor suppression. Task-irrelevant distractors that share features with the target induce significant interference, supporting the dimension-weighting (Found & Müller, 1996; Liesefeld & Müller, 2019) and modality-weighting theories (Töllner et al., 2009a). The N2pc component indicated attentional engagement, particularly with feature-sharing distractors, and interference increased with extended exposure. We acknowledge ongoing debates about the P_D component's role, suggesting it may represent attentional disengagement rather than active suppression. Further research is needed to explore these interpretations. To establish causal evidence for distractor suppression, integrating EEG with brain stimulation techniques (e.g., TMS or tACS) is crucial. Advanced EEG analyses, such as phase-amplitude coupling and brain connectivity, can provide deeper insights into neural dynamics beyond current focus areas. This knowledge could be pivotal for clinical applications, such as developing diagnostic indices of attentional performance and creating brain stimulation protocols to enhance attentional control.

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Curriculum Vitae

Shao-Yang Tsai

CURRENT POSITION

PhD Student (Advisors: Zhuanghua Shi and Hermann Müller)
Department of Experimental Psychology and Graduate School of Systemic Neurosciences,
Ludwig-Maximilians-Universität München, Munich, Germany Oct. 2019 — July.2024

EDUCATION

Master of Science (Major: Cognitive Neuroscience; Advisors: Wei-Kuang Liang and Chi-Hung Juan)
National Central University, Taoyuan, Taiwan Feb. 2015 — Nov. 2017
Bachelor of Science (Double major: 1. Counseling and Clinical Psychology 2. Life Science)
National Dong Hwa University, Hualien, Taiwan Sep. 2007 — Jun. 2012
Senior High School
National Hsinchu Senior High School, Hsinchu, Taiwan Sep. 2004 — Jun.2007

WORK EXPERIENCE

Research Assistant Aug. 2013 — Feb. 2015, Mar. 2018 — July 2019
Visual Cognition Lab, National Central University, Taoyuan, Taiwan (PIs: Chi-Hung Juan and Neil Muggleton)
Teaching Assistant (Courses: 1. The Learning Brain 2. General Psychology) Feb. 2015 — Jun. 2016
Institute of Cognitive Neuroscience, National Central University, Taoyuan, Taiwan
Research Assistant Sep. 2013 — July 2014
Psychiatry Department of Taipei Veterans General Hospital, Taipei, Taiwan (PI: Cheng-Ta Li; cooperates with Chi-Hung Juan)
Psychological Counselor (military service) Dec. 2012 — Aug. 2013
Mental Health Center, the Republic of China Army (Taiwan)

PUBLICATIONS

1. **Tsai**, Nasemann, Qiu, Töllner, Müller & Shi (2023) **Little engagement of attention by salient distractors defined in a different dimension or modality to the visual search target.** Psychophysiology. doi: 10.1111/psyp.14375
2. Qiu, Zhang, Allenmark, Nasemann, **Tsai**, Müller & Shi (2023) **Long-term (statistically learnt) and short-term (inter-trial) distractor-location effects arise at different pre- and post-selective processing stages.** Psychophysiology. doi: 10.1111/psyp.14351.
3. Jaiswal, **Tsai**, Juan. Muggleton & Liang (2019). **Low delta and high alpha power are associated with better conflict control and working memory in high mindfulness, low anxiety individuals**. Soc Cogn Affect Neurosci, 14, 6. doi: 10.1093/scan/nsz038
4. **Tsai**, Jaiswal, Chang, Liang, Muggleton & Juan (2018). **Meditation Effects on the Control of Involuntary Contingent Reorienting Revealed with Electroencephalographic and Behavioral Evidence.** Front Integr Neurosci, 12, 17. doi:10.3389/fnint.2018.00017
5. Jaiswal, **Tsai**, Juan, Liang, & Muggleton (2018). **Better Cognitive Performance Is Associated with the Combination of High Trait Mindfulness and Low Trait Anxiety.** Front Psychol, 9, 627. doi:10.3389/fpsyg.2018.00627

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1. Shao-Yang Tsai, Jan Nasemann, Hermann Müller, Zhuanghua Shi (July 2022) **Distractors shared more target features attract more attention reflected in N2pc.** The Federation of European Neuroscience Societies 2022 Annual Meeting. Paris, France. (Poster)
2. Shao-Yang Tsai, Jan Nasemann, Hermann Müller, Zhuanghua Shi (June 2022) **Salient distractors capture attention without engagement: A cross-modal EEG study.** The Organization for Human Brain Mapping 2022 Annual Meeting. Glasgow, UK. (Poster)
3. Shao-Yang Tsai, Satish Jaiswal, Chi-Fu Chang, Chi-Hung Juan, Wei-Kuang Liang (Jan. 2018). **Practice-Related**

Changes in Attentional Control of Contingent Reorienting Revealed by EEG Oscillations. Taiwan Society of Cognitive Neuroscience 2018 Annual Meeting. Taichung, Taiwan. (Poster)

4. Shao-Yang Tsai, Satish Jaiswal, Chi-Hung Juan, Wei-Kuang Liang (Mar. 2017). **Meditation Effects on Involuntary Control of Attentional Orienting.** Cognitive Neuroscience Society 24th Annual Meeting. San Francisco, California, USA. (Poster)
5. Shao-Yang Tsai, Satish Jaiswal, Chi-Hung Juan, Wei-Kuang Liang (Jan. 2017). **The effect of meditation on attentional capture in a rapid serial visual presentation task.** Taiwan Society of Cognitive Neuroscience 2017 Annual Meeting. Taoyuan, Taiwan. (Poster)
6. Shao-Yang Tsai, Satish Jaiswal, Shih-Lin Huang, Wei-Kuang Liang and Chi-Hung Juan (Jan. 2016). **Meditation Modulates Visual Attention in Contingent Reorienting: An integrated approach with EEG and attentional capture task to investigate the neural mechanisms of meditation.** Taiwan Society of Cognitive Neuroscience 2016 Annual Meeting. Taipei, Taiwan. (Poster)
7. Yu-Ju Chou, Shao-Yang Tsai, Yung-Sheng Wen (Oct. 2012). **Using Transcranial Magnetic Stimulation on RTPJ Affects Moral Judgment.** 51st Annual Meeting of the Taiwanese Psychology Association, Taichung, Taiwan.
8. Shao-Yang Tsai, Kai-Lun Hsieh, Shiau-Hwa, Liu. (Jun. 2012) **Exposure to Emotional Films Modulates Late Positive Potentials as Viewing Pictures of Same Emotion.** 18th Annual meeting of the Organization for Human Brain Mapping. Beijing, China. (Poster)
9. Shao-Yang Tsai, Chia-Hsuan Hu, Kai-Lun Hsieh, Ching Hua Li, Yung-Sheng Wen, Yu-Ju Chou (Nov. 2010) **TMS may change people's moral judgment to the innocents: A TMS study on the rTPJ region of the human brain.** 49th Annual Meeting of the Taiwanese Psychology Association, Chia-Yi, Taiwan. (Poster)
10. Shao-Yang Tsai, Pei-Hsuan Chen, Shin-Yian Tsai, Yu-Chen Li, Shiau-Hua Liu. (Aug. 2010) **The Effect and Fitness of Emotion Regulation on Different Negative Emotions.** The International Conference of 4th Asian Congress of Health Psychology. Taipei, Taiwan. (Poster)

HONORS

The Su Shiang-Yeu Master's Thesis Award, Taiwanese Psychological Association, Taiwan, 2018
Recognized as one of the most prominent psychology graduates in Taiwan for the year based on the quality of the dissertation.

The Phi Tau Phi Scholastic Honor Society of the Republic of China (Taiwan), 2016
Awarded to the top graduates in each college of a university.

Distinguished Service Award, National Dong Hwa University, Taiwan, 2010
Honored for significant volunteer contributions to the university.

SKILLS

Experimental skills: Behavioral and Physiological Measurements (EEG, ECG, MRI), Brain stimulations (TMS/tDCS/tACS)

Computational and data analysis skills: Matlab (psychtoolbox; EEG data processing: SPM, Neuroholo, EEGLab, fieldtrip), Python, SPSS, JASP

LANGUAGES

Chinese (native)
English
Taiwanese

Publications

1. **Tsai**, Nasemann, Qiu, Töllner, Müller & Shi (2023) Little engagement of attention by salient distractors defined in a different dimension or modality to the visual search target. Psychophysiology. doi: 10.1111/psyp.14375

2. Qiu, Zhang, Allenmark, Nasemann, **Tsai**, Müller & Shi (2023) Long-term (statistically learnt) and short-term (inter-trial) distractor-location effects arise at different pre- and post-selective processing stages. Psychophysiology. doi: 10.1111/psyp.14351.

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Declaration of Author Contributions

Chapter 2 (Study 1):

Tsai, S.-Y., Nasemann, J., Qiu, N., Töllner, T., Müller, H. J., & Shi, Z. (2023). Little engagement of attention by salient distractors defined in a different dimension or modality to the visual search target. *Psychophysiology*, 00, e14375. https://doi.org/10.1111/psyp.14375

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.

My contribution to this publication in detail:

When I joined the Munich team, I started my first cross-modal attention study. I began collecting data in November 2019 and faced several technical problems, like tactile vibration signals being wrongly recorded by EEG channels. I fixed these issues by carefully working through them. During the COVID-19 lockdown, I focused on data analysis using tools like BVA from Brain Products, Fieldtrip, and EEGLAB. The cross-modal settings caused unexpected noise, but I found the ICA method from EEGLAB effective for reducing it.

Working with my supervisors, colleagues, and experts during events like the GSN retreat and conferences provided valuable feedback that helped improve our results. I took the lead in creating detailed visual representations of our findings and wrote the initial manuscript draft. Throughout the review process, I worked closely with co-authors, making necessary revisions. Additionally, I conducted further experiments as suggested by reviewers to strengthen our conclusions.

Chapter 3 (Study 2):

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

Chapter 4 (Study 3):

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

My contribution to Study 2 and Study 3 in detail:

Based on findings and unresolved questions from our initial study, I designed and conducted Studies 2 (September 2020) and 3 (March 2021). These studies addressed specific ambiguities, such as the origin of event-related lateralization due to lateralized stimuli in the first study.

With insights from the first study, I carried out the experiments effectively, ensuring higher data quality. After the COVID-19 pandemic, I presented preliminary findings at several in-person conferences. Constructive feedback from supervisors, peers, and experts prompted additional analyses and refined interpretations. Like the first study, I led the visualization of results and initial drafting for both studies. I collaborated closely with co-authors, implementing revisions to enrich the content. Currently (July, 2024), we are refining the manuscript for submission to peer-reviewed journals.

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Signatures:

Shao-Yang Tsai: ______________________________ Date: ___________

Supervisor: _______________________ Date: ___________

Affidavit Dissertation

Eidesstattliche Versicherung/Affidavit
(Studierende / Student)

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation
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selbstständig angefertigt habe, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

I hereby confirm that the dissertation The Neural Correlates of Distractor Handling in Cross-Modal Search
is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

München / Munich
12.09.2023 Shao-Yang Tsai
(Datum / Date) (Unterschrift / Signature)