The P$_D$ Component and the Inhibition of Distracting Stimuli

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Abstract

There has been a long-lasting debate about whether salient stimuli, such as uniquely colored objects, have the ability to automatically distract us. To resolve this debate, it has been suggested that salient stimuli do attract attention, but that they can be suppressed to prevent distraction. Some research supporting this viewpoint has focused on a newly discovered event-related-potential (ERP) component called the distractor positivity (P_D), which is thought to measure an inhibitory attentional process. This collaborative review summarizes previous research relying on this component with a specific emphasis on how the P_D has been used to understand the ability to ignore distracting stimuli. In particular, we outline how the P_D component has been used to gain theoretical insights about how search strategy and learning can influence distraction. We also review alternative accounts of the cognitive processes indexed by the P_D component. Ultimately, we conclude that the P_D component is a useful tool for understanding inhibitory processes related to distraction and may prove to be useful in other areas of study related to cognitive control.

Keywords: P_D, distractor positivity, distraction, inhibition, attentional capture, event-related potentials

The P$_D$ Component and the Inhibition of Distracting Stimuli

Our attentional systems are constantly bombarded by salient stimuli that have been designed to attract our attention. From neon construction cones on the roadside to pop-up notifications on our cell phones, our attentional systems must make split-second decisions to determine which stimuli in our environments are relevant to our immediate goals and which are just distractions. For this reason, visual warning signals are often designed to be physically salient, using bright colors or flashing lights to attract attention.

Formal research on *attentional capture*, however, has painted a more complex picture. There has been a longstanding debate about whether salient stimuli have an ability to involuntarily attract attention (see review by Luck et al., 2021). As a resolution, it has been suggested that salient stimuli might have the potential power to capture attention, but that capture can be reduced via an inhibitory mechanism (Gaspelin & Luck, 2018c, 2019). One line of support for this inhibitory process has come from event-related potential (ERP) studies of the *distractor positivity (P$_D$) component*, which has been proposed to measure suppression of salient distracting stimuli. For example, Figure 1 depicts a version of commonly used task to study visual distraction in which participants searched for a target stimulus and attempted to ignore a salient distractor that was uniquely colored. Behavioral performance indicated that the salient distractor was successfully ignored. As can be seen in the ERPs, there was a positivity occurring in electrode sites of

visual cortex that were contralateral to the salient distractor relative to ipsilateral electrodes. This P$_D$ component can be more easily seen in the contralateral-minus-ipsilateral difference waveform. It has been suggested to be a neural marker of an inhibitory process that was used to prevent distraction by the salient distractor.

The P$_D$ component has been studied in a variety of visual search tasks and comes in many different shapes and sizes (see Figure 2). As a result, there are differing viewpoints about what exactly the P$_D$ component indicates and what this means about the underlying architecture of visuospatial attention. This collaborative review provides an overview of the P$_D$ component with a specific emphasis on how this ERP component has been used to study inhibition of distracting stimuli. Authors with a variety of viewpoints outline recent advances that have been made using the P$_D$ component in subtopics related to their specific expertise, allowing the reader to gain a broader perspective of the P$_D$ component than would be possible from a single author. In the following sections, we discuss previous research that has linked the P$_D$ to suppression of salient distractors, as well as insights that the field of attentional capture has gained from this research. Ultimately, we conclude that the P$_D$ component is an ERP measure of attentional orienting that could provide valuable insights into other areas related to cognitive control and inhibition.
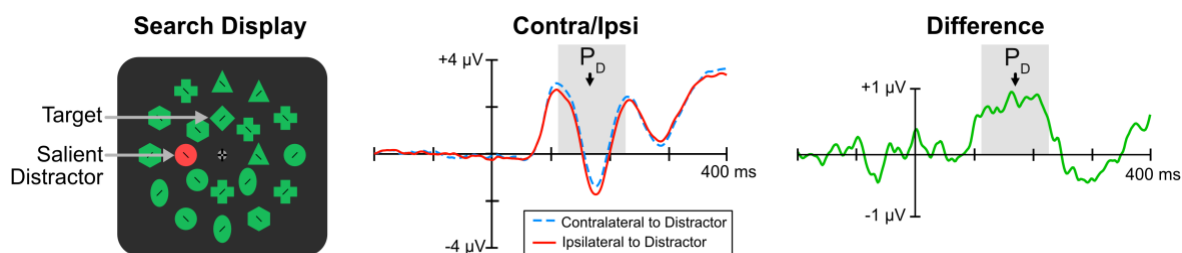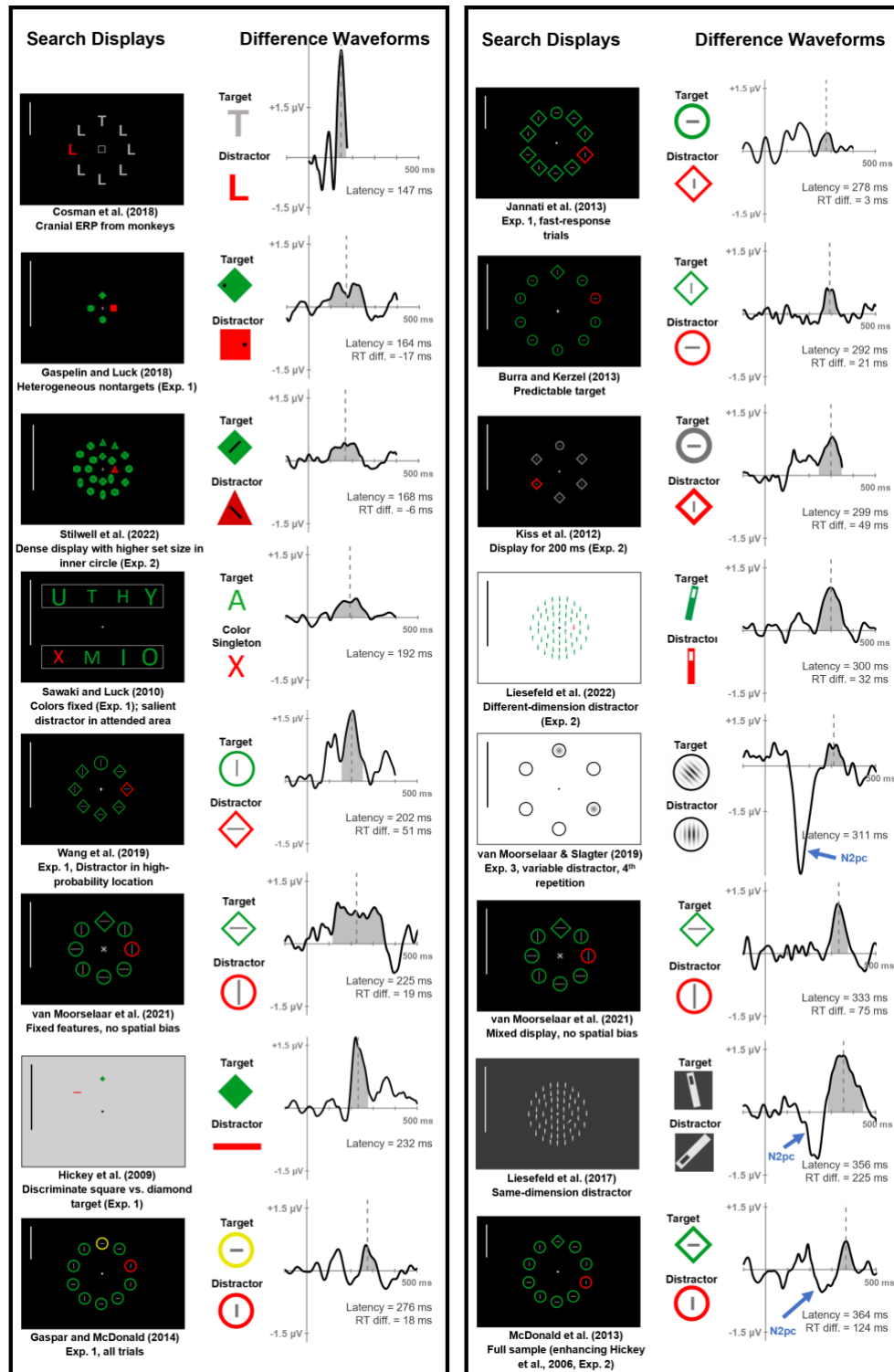

Figure 1. An example of an attentional capture task and P$_D$ component (from Stilwell, Egeth, & Gaspelin, 2022, Exp. 2). Participants searched for a specific shape and attempted to ignore a salient distractor. There was a positive-going deflection in electrode sites over visual cortex that were contralateral to the salient distractor. This P$_D$ component can be more clearly seen as a contralateral-minus-ipsilateral difference waveform (green line). The time window used in the analysis is shown in gray.

Figure 2. Stimuli and the resulting P_D components, sorted by their latency, from several studies of attentional capture. As can be seen, the magnitude, latency, and shape of the P_D component vary substantially as a function of the search task. All ERPs are contra-minus-ipsi difference waveforms. For comparison, displays are drawn to either one of two scales (where available) with the gray vertical bar in the upper left of each panel indicating 10° of visual angle. AUC = Area under the curve (indicated by the gray shading): the area bounded by the displayed grand-average ERP, the x-axis and the onset and offset at 30% peak amplitude of the component that was interpreted as the P_D in the respective publication; Latency = the time point that divides that area into two equal halves (50%-area latency); RT diff. = the distractor effect (distractor-present minus distractor-absent) with negative values indicating distractor benefits and positive values indicating distractor costs on RTs. Note: In Cosman et al. (2018), the stimuli were presented from 6° to 12° eccentricity (9° represented here) depending on the eccentricity of the receptive fields of most of the recorded neurons on each day. The ERPs were digitized from the original manuscripts using WebPlotDigitizer (Rohatgi, 2022) and interpolated to 1000 Hz before visualization and calculation of AUC and latency.

The N2pc and P$_D$ Components
by Nicholas Gaspelin

Before explaining the P$_D$ component, it will help to first explain the *N2 posterior contralateral (N2pc)* component. The N2pc has been proposed as a measure of attentional allocation to a visual stimulus in a given hemifield. It appears in posterior electrode sites over visual cortex (e.g., PO7/PO8) about 200–300 ms after the appearance of the search display and is a negative-going deflection that is larger in the hemisphere contralateral to the attended stimulus than in the ipsilateral hemisphere. For example, Luck and Hillyard (1990) had participants search for a triangle target amongst a set of arrows and report whether the target was present or absent. Eye movements were prohibited in this task and participants were therefore required to use covert attention to find the target. When the target appeared in the left hemifield, there was a greater negativity in electrode sites over right visual cortex than over left visual cortex. Similarly, when the target appeared in the right hemifield, there was a greater negativity in electrode sites over left visual cortex than over right visual cortex. This N2pc component was interpreted as a measure of a covert attentional process that was used to find the target stimulus in the search displays.

Most now agree that the N2pc reflects some aspect of covert attentional allocation (see review by Luck, 2012). Famously, Luck and Hillyard (1994b) proposed that the N2pc reflects filtering of distractors around the attended location, based upon the observation that the N2pc is often largest when the attended location is surrounded by distractors that must be rejected (Bacigalupo & Luck, 2015; Luck et al., 1997; Luck & Ford, 1998; Luck & Hillyard, 1994a; Woodman & Luck, 1999). However, this interpretation has been questioned, due to evidence that an N2pc can also occur when distractor filtering is seemingly unnecessary (Eimer, 1996; Mazza et al., 2009b, 2009a). As a result, other interpretations of the N2pc have been proposed, which mostly assume that the N2pc reflects some other aspect of attentional allocation, such as the shifting of attention (Tan & Wyble, 2015) or the extraction of information at the attended location (Foster et al., 2020; Wyble et al., 2020; Zivony et al., 2018).

The *distractor positivity (P$_D$)* component is, in many ways, the opposite of the N2pc component. Rather than measuring attentional allocation to a given stimulus, it has been proposed to measure suppression of a given stimulus. Like the N2pc, it appears at posterior electrode sites over visual cortex (e.g., PO7/PO8). Unlike the N2pc, it is a *positive-going* deflection (rather than a negative-going deflection) in the contralateral electrode sites compared to ipsilateral electrode sites. For this reason, the P$_D$ has been assumed to be related to
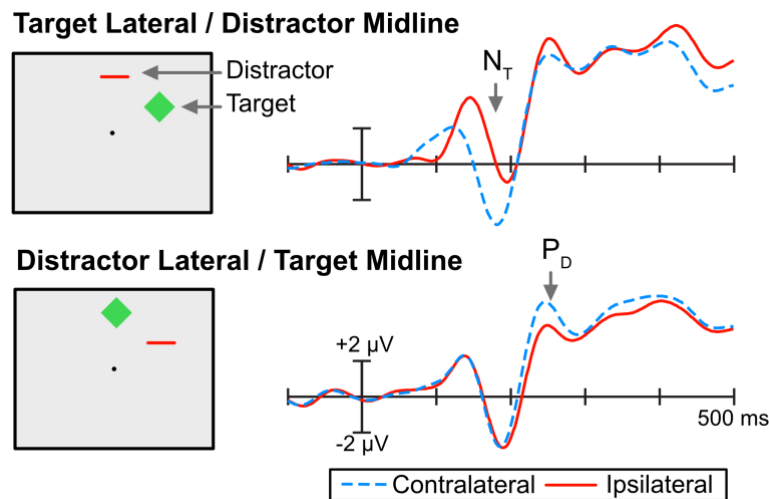

Figure 3. Stimuli and results from Hickey, Di Lollo, and McDonald (2009, Exp. 1). This was the first study to demonstrate a P$_D$ component to a distractor stimulus.

attentional suppression, rather than attentional enhancement of a stimulus.

The P_D was first identified by Hickey and colleagues (2009) who had participants search for a green diamond and ignore a red line distractor (Figure 3). The stimuli were arranged so that, on some trials, one item appeared on the vertical midline (i.e., directly above or below the central fixation point) and the other was lateralized. Because any item on the vertical midline is equally represented in both hemispheres, any lateralized activity from a midline item will effectively cancel out, allowing one to isolate ERP components to the lateralized stimulus. On target lateral/distractor midline trials, there was a negative-going deflection contralateral to the target (a *target negativity*; N_T), which was taken to indicate attentional allocation to the target, similar to the N2pc. On distractor lateral/target midline trials, however, there was a positive-going deflection contralateral to the distractor (a *distractor positivity*; P_D). A control experiment suggested that this lateralized positivity was not due to low-level sensory imbalances caused by presenting a lone item in one visual hemifield. The authors therefore reasoned that this newly discovered P_D component reflected suppression of the distractor stimulus, which was task-irrelevant and needed to be ignored to perform the task (see also Hilimire et al., 2012).[1]

The P_D component can occur in the time range between 100 to 500 ms, which is more variable than the timing of the N2pc component (200–300 ms). This might be related to the fact that suppression can occur either before or after the first shift of attention. Specifically, if suppression occurs *before* the first shift of attention, the P_D component may occur relatively early (e.g., 100–275 ms), either before or during the N2pc time window (e.g., Gaspar & McDonald, 2014; Sawaki & Luck, 2010). This "early" P_D component is often interpreted as a suppressive process that

preemptively prevents attentional allocation to a stimulus. If suppression occurs *after* a stimulus is first attended, however, the P_D may occur at later time windows (e.g., 275–500 ms), after an N2pc is elicited by the stimulus. This "late" P_D component is often interpreted as a suppressive process involved in terminating attentional allocation to a stimulus (Drisdelle et al., 2023; Hilimire et al., 2011; Liesefeld et al., 2017; Sawaki & Luck, 2013).[2] In short, the P_D component can have a variable latency, and as is shown in the following sections, this is important to consider when interpreting this component.

In sum, the N2pc and P_D are highly related ERP components. They both are visually evoked components that occur at posterior electrode sites over visual cortex and are related to attentional processes that occur in vision. Whereas the N2pc is presumed to reflect attentional allocation to a stimulus, the P_D is presumed to reflect attentional suppression of a stimulus.

The Attentional Capture Debate
by Nicholas Gaspelin and Dominique Lamy

In attention research, there has been a longstanding debate about whether salient stimuli can involuntarily distract us even when they are task irrelevant. Here, a *salient stimulus* is defined as an object that contrasts with neighboring objects (or the background) on a low-level feature dimension, such as color or orientation (Nothdurft, 1993). For example, a lone red object amongst a set of homogenously colored green objects (called a *color singleton*) would be considered highly salient. Historically, the attentional capture debate was divided into two opposing viewpoints: stimulus-driven and goal-driven accounts.

Stimulus-driven accounts proposed that certain kinds of salient stimuli will automatically capture attention regardless of the observer's goals

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[1] More specifically, Hickey et al. (2009) proposed that the N_T and P_D are subcomponents that summate to form the N2pc component. This summation would occur in tasks where the target appears in one hemifield and the distractor appears in the opposing hemifield, resulting in a negative-going deflection (N_T) in electrodes contralateral to the target and a positive-going deflection (P_D) in electrodes contralateral to the distractor. Because the two objects are in opposite hemifields, these two components would summate to produce a large, lateralized negativity (i.e., an N2pc) with respect to the target. For example, a P_D to a distractor in the right hemifield would summate algebraically with an N_T to the target in the left hemifield to produce a large N2pc. For a more detailed explanation, see the original article.

[2] Some initial studies called this late lateralized positivity a PTC component. However, later studies showed that this positivity shares many similarities with the P_D component, hence the name "late" P_D.
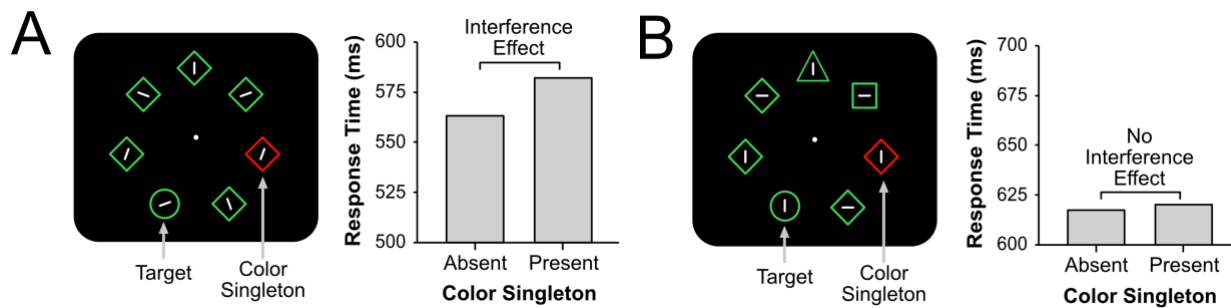
Figure 4. Conflicting behavioral results in the attentional capture debate. (A) Theeuwes (1992, Exp. 1) had participants search for a popout shape and ignore a salient color singleton. This yielded a distractor interference effect, supporting stimulus-driven accounts. (B) Bacon and Egeth (1994, Exp. 3) adapted the displays to use heterogeneous distractor shapes (e.g., triangles, diamonds, and squares) to prevent participants from searching for a popout shape. Supporting goal-driven accounts, this manipulation eliminated the interference effect, even on a subset of trials that used displays like those shown in (A).

or intentions (Franconeri & Simons, 2003; Jonides & Yantis, 1988; Theeuwes, 1992; Yantis & Jonides, 1984). For example, Theeuwes (1992, Exp. 1) devised the *additional singleton paradigm,* in which participants searched for a circle target among diamonds and reported the orientation of a line inside the target (Figure 4A). On some trials, one of the diamonds was uniquely colored (i.e., a color singleton). Response times (RTs) were slower when the singleton distractor was present compared to when it was absent. This interference effect was taken to indicate that the task-irrelevant color singleton automatically captured attention, slowing detection of the target when it was present.

Goal-driven accounts, however, proposed that salient stimuli have no automatic power to attract attention and that attentional selection is instead driven by the intentions of the observer (Folk et al., 1992). According to this account, participants first establish an attentional template for the target features and only stimuli matching this attentional template capture attention. Initial support for this account largely came from a modified spatial cueing paradigm, in which participants searched displays for a target of a specific color (e.g., red letter) and attempted to ignore a salient cue that appeared before the search display. Importantly, this cue could either match or mismatch the target color. Several studies showed that matching cues produced cue validity effects (i.e., better performance when the target appeared at the cue location vs. elsewhere), indicative of capture, whereas mismatching cues did not (e.g., Folk et al., 1992; Folk & Remington, 1998; see also Becker et

al., 2010). This *contingent capture effect* has been taken to suggest that salient stimuli do not have inherent power to attract attention and will only capture attention if they match the immediate goals of the observer.

Furthermore, goal-driven accounts suggested that previous studies supporting stimulus-driven accounts may have encouraged a strategy whereby participants established an attentional template for any kind of feature singleton (a strategy called *singleton-detection mode*; Bacon & Egeth, 1994). For example, in the study shown in Figure 4A, the target was a shape singleton, and this may have encouraged participants to look for any unique "popout" stimulus. As evidence of this, several studies have shown that when participants are instead encouraged to search for a specific shape rather than for a singleton (a strategy called *feature-search mode*; Figure 4B), interference effects on manual RT from color-singleton distractors can be largely eliminated (e.g., Bacon & Egeth, 1994; Lamy & Egeth, 2003; Leber & Egeth, 2006). Such findings were taken as additional evidence that attentional capture may be limited to situations in which the salient stimulus matches the intentions of the observer, consistent with goal-driven models.

Initial ERP studies of attentional capture largely paralleled the behavioral studies of attentional capture. These studies tested whether or not salient distractors elicited an N2pc component, as a measure of whether they captured attention. For example, Hickey et al. (2006) used a task similar to Theeuwes (1992) in which participants

searched for a popout target on the shape dimension and attempted to ignore a color-singleton distractor (Figure 4A). Color-singleton distractors elicited an N2pc component, suggesting that they captured attention, and this finding was taken to support stimulus-driven accounts (but see McDonald et al., 2013). Other ERP studies, however, produced opposite results. For example, Lien and colleagues (2008) used a spatial-cueing paradigm in which participants searched for a target of a specific color and ignored a salient but irrelevant cue. Salient cues that matched the target color elicited an N2pc component, whereas salient cues that mismatched the target color did not. These findings were taken to suggest that salient stimuli capture attention only when they match the attentional template of the observer, consistent with goal-driven accounts (see also Lien et al., 2010). Altogether, the N2pc-component studies resulted in the same kind of stalemate as the behavioral studies.

In sum, the attentional capture debate has been extraordinarily challenging to resolve. Each theoretical camp has been equally well-supported empirically and has typically relied on a unique set of tasks, making it difficult to pinpoint why opposing results were obtained. This state of affairs has laid the groundwork for a debate that has lasted several decades without a coherent resolution.

The Signal Suppression Hypothesis
by Nicholas Gaspelin

As an attempt to resolve this debate, Sawaki and Luck (2010) proposed that suppression could provide a framework for understanding when salient distractors will automatically capture attention and when they will be ignored. Specifically, they proposed the *signal suppression hypothesis*, whereby salient stimuli produce a bottom-up "attend-to-me" signal that competes for attention, consistent with stimulus-driven accounts, yet this salience signal can be overridden by an inhibitory process that prevents attentional capture, consistent with goal-driven accounts. They suggested that suppression of salient distractors could be measured by the P_D component.

To test this hypothesis, Sawaki and Luck (2010) had participants search for a target letter (e.g., a small green A) amongst green distractor letters (Figure 5). On some trials, the target was present. On other trials, the target was absent, and a distractor appeared at a lateralized location. This distractor could either be a target-similar distractor, which was the target letter in the wrong font size (e.g., large green A), or a singleton distractor, which was a random letter in a unique color (e.g., a red X). Targets elicited an N2pc component suggesting that they were attended. Target-similar distractors also elicited an N2pc component, suggesting that they captured attention consistent with a goal-driven account. Crucially, singleton distractors did not elicit an N2pc component and instead elicited a P_D component. Given the previous association of the P_D component with distractor suppression (Hickey et al., 2009), this pattern of results was taken to indicate that the singleton distractor was suppressed preemptively (i.e., before the first shift of attention) in order to prevent attentional capture. Follow-up experiments replicated this basic pattern of results and ruled out the possibility that the lateralized positivity (i.e., the P_D) was due to an imbalance in sensory energy.

Several subsequent ERP studies provided additional evidence that the P_D component reflects a suppression of salient distractors to prevent attentional capture. For example, Gaspar and McDonald (2014, Exp. 1) had participants search for a yellow target amongst green items, while ignoring a red singleton distractor. Singleton distractors elicited a P_D component and no corresponding N2pc component, suggesting that the distractor was suppressed to prevent attentional capture (similar to Sawaki & Luck, 2010). In addition, the magnitude of the P_D component was found to be larger on fast-response trials than on slow-response trials, suggesting that successful suppression of the salient distractor allowed the target to be found more quickly (see also Jannati et al., 2013). Other studies found that the P_D component elicited by salient distractors emerged only when the search array duration was short (200 ms instead of until response), suggesting that pressure to quickly locate the target incentivized participants to suppress the salient distractor (Kiss et al., 2012). All of these findings are consistent with the idea that the P_D component indicates some kind of process involved in the suppression of salient distractors.

Additional support that the P_D component reflects suppression has come from studies that combine ERPs with other methodologies. For
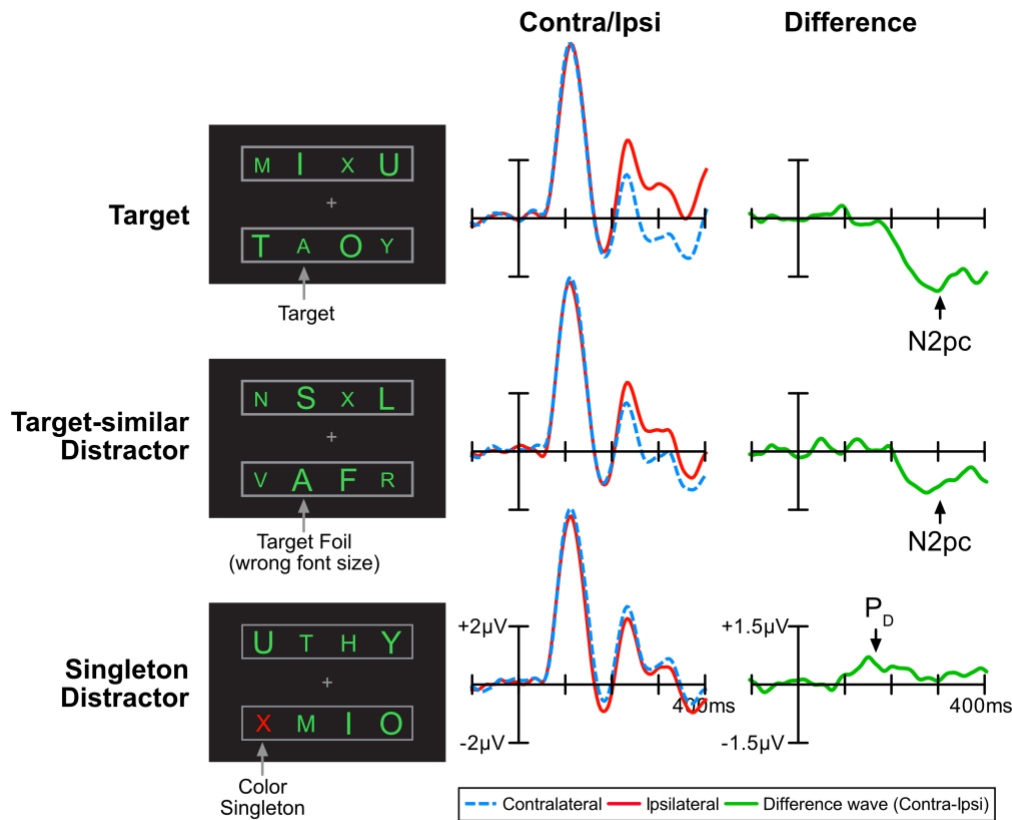
Figure 5. Stimuli and results from Sawaki and Luck (2010, Exp. 2). Targets and target-similar distractors elicited an N2pc, whereas singleton distractors elicited a P$_D$ component, which was taken to suggest that the color singleton was suppressed.

example, Cosman and colleagues (2018) found evidence from single-unit recordings in nonhuman primates that neurons in the frontal eye fields had lower discharge rates for salient distractors than the baseline rate observed for nonsalient distractors (a suppression effect). This same study also found evidence of a monkey homologue to the P$_D$ component that was observed in ERPs recorded from extrastriate cortex. In addition, Weaver and colleagues (2017) conducted a study that concurrently measured EEG and eye tracking in humans performing an attentional capture task. They reported a P$_D$ component that occurred before eye movements that were successfully directed away from the salient distractor, and the magnitude of this P$_D$ component was positively correlated with the degree of curvature of eye movements away from the salient distractor. Both findings are consistent with the idea that suppression via covert

attention was used to guide eye movements away from the salient distractor.

Further support for the signal suppression hypothesis that does not rely on ERPs has come from a variety of behavioral paradigms. For instance, in the *capture-probe paradigm* (Gaspelin et al., 2015), participants search displays for a target shape (e.g., a green diamond) and attempt to ignore a singleton distractor. On a subset of trials, letters are superimposed over each shape of the search display and participants attempt to report as many letters as they saw (Figure 6A). The key finding is that probe recall is impaired at the location of the singleton distractor compared to nonsingleton distractors, consistent with the idea that a suppressive process was applied to the salient distractor to prevent capture (Figure 6B; see also Chang & Egeth, 2019, 2021; Gaspelin & Luck,
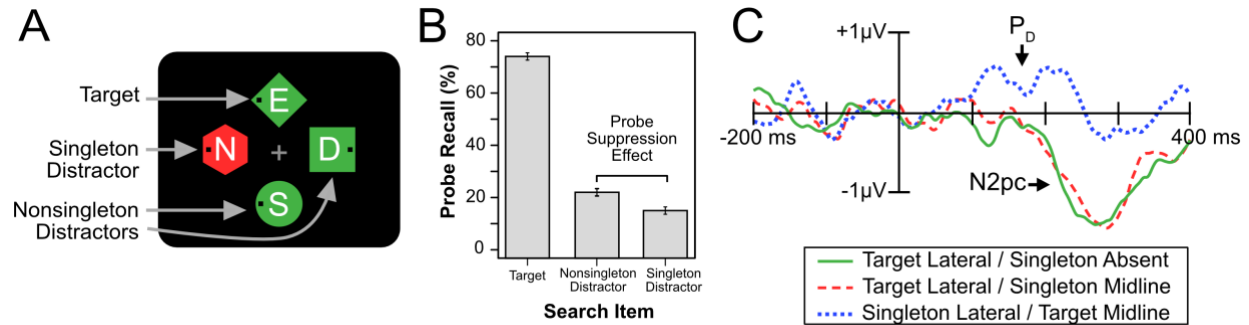
Figure 6. Stimuli and results from Gaspelin and Luck (2018, Exp. 1). (A) Search displays from the experiment. (B) Probe recall at the singleton distractor was below the baseline level of the average nonsingleton distractor (a probe suppression effect). (C) Ipsilateral-minus-contralateral difference ERP waveforms for each trial type. ERPs from singleton distractors (singleton lateral / target midline) showed a P_D component indicating suppression. ERPs from targets (target lateral trials) showed an N2pc that was unaffected by singleton presence.

2018a, 2018b; Lien et al., 2022; Stilwell & Gaspelin, 2021; but see Oxner et al., 2022). Similarly, other studies measured shifts of gaze and demonstrated that eye movements were directed to the salient distractor at below-baseline levels (Adams et al., 2022; Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018a; Hamblin-Frohman et al., 2022; Stilwell et al., 2023). In addition, several studies showed that observers gradually learn to suppress salient distractors based upon their specific features (Gaspelin & Luck, 2018a; Ramgir & Lamy, 2022; Stilwell et al., 2019; Vatterott & Vecera, 2012; Gaspelin et al., 2019), spatial locations (Goschy et al., 2014; Ruthruff & Gaspelin, 2018; Sauter et al., 2018; Wang & Theeuwes, 2018b, 2018a), and general status as a distractor (Ma & Abrams, 2022, 2023; Vatterott et al., 2018; Won et al., 2019; Won & Geng, 2020). All of these behavioral studies provided converging evidence that some kind of suppressive process can be applied to salient distractors using experimental paradigms very similar to those used to study the P_D component.

Later studies provided a more direct linkage between attentional suppression and the P_D component by combining behavioral approaches to study suppression with ERP approaches (Gaspelin & Luck, 2018b; see also Feldmann-Wüstefeld et al., 2020). For example, using the capture-probe paradigm, Gaspelin and Luck (2018b) found below-baseline probe reports at the location of the singleton distractor (Figure 6B), as well as a P_D component associated with the singleton distractor

(Figure 6C). Crucially, the magnitude of the P_D component and probe-based suppression effects were correlated: participants who had large probe-based suppression effects also showed large P_D components. This finding demonstrates a direct association between the P_D component and the suppression of covert shifts of visual attention. Indeed, recent computational models of visual attention that have an inhibitory component are able to simulate a P_D component and several other behavioral measures of suppression (Wyble et al., 2020).

In sum, there is considerable evidence that salient distractors can be suppressed to prevent attentional capture (see also reviews by Gaspelin & Luck, 2018c, 2019). Some of this evidence has come from the P_D component, which is thought to index an inhibitory process in attention (but see section on "Alternative Accounts"), as well as from several converging lines of evidence from other methodologies (e.g., single-unit recordings, psychophysics, eye tracking, and computational modeling).

Search Strategy: Feature-Search and Singleton-Detection Mode
by Brad T. Stilwell, Dirk Kerzel, and Howard E. Egeth

As previously reviewed, there is evidence that search strategy can strongly influence suppression

of salient distractors.[3] Tasks with "popout" targets can induce participants to adopt a more general attentional set for salient stimuli (Bacon & Egeth, 1994; Gaspelin et al., 2015, 2017; Kerzel & Barras, 2016; Leber & Egeth, 2006; Stilwell & Gaspelin, 2021). This *singleton-detection mode* strategy (Figure 4A) can be prevented by using tasks that encourage a *feature-search mode* strategy (Figure 4B). Typically, search tasks that encourage singleton-detection mode yield attentional capture by salient distractors, whereas tasks that encourage feature-search mode yield no attentional capture by salient distractors. Although there has been some debate about the underlying mechanisms that lead to this difference (e.g., Gaspelin et al., 2023; Leber & Egeth, 2006; Liesefeld & Müller, 2023; Theeuwes, 2004, 2022), it is abundantly clear that tasks in which the target is most often a singleton encourage attentional capture via strategic changes in how participants search displays.

The P_D component has provided some evidence consistent with a difference in capture based on the type of strategy afforded by the task. Several studies have shown that salient distractors elicit a P_D component in heterogeneous displays that encourage feature-search mode (Drisdelle & Eimer, 2021; Gaspelin & Luck, 2018b; Sawaki & Luck, 2010; but see Barras & Kerzel, 2016) and this suppression occurs even when distractors are highly salient (Drisdelle & Eimer, 2023; Stilwell et al., 2022). However, studies using homogenous displays have found more mixed results. If the target shape is *predictable* (e.g., always a circle), the participant can perform the task correctly by using either feature-search mode or singleton-detection mode. This has been called an "option trial" because the participant has the option to employ either strategy (e.g., Leber & Egeth, 2006). In this case, salient distractors mostly elicit a P_D component (Barras & Kerzel, 2016; Burra & Kerzel, 2013; Feldmann-Wüstefeld et al., 2021;

Gaspar & McDonald, 2014; Jannati et al., 2013; Moorselaar et al., 2021), but may elicit an N2pc component in a subset of trials (McDonald et al., 2013). However, if the target is *unpredictable* (e.g., a circle amongst diamond distractors or diamond amongst circle distractors, randomly intermixed), it will be disadvantageous to locate the target via feature-search mode, and participants will be forced to use singleton-detection mode to complete the search. In such cases, N2pc components were often found to be elicited by salient distractors (Burra & Kerzel, 2013; Hickey et al., 2006; Hilimire et al., 2011; but see McDonald et al., 2013; Moorselaar et al., 2021). Therefore, the type of strategy employed by participants is heavily influenced by the type of search display and by the predictability of the target. Both can influence the strategy adopted by observers and should be considered when designing attentional capture studies measuring ERP components.

It is worth noting that the adoption of these control settings might be flexible. In tasks that use option trials, some participants might adopt either feature-search or singleton-detection mode for the entire experiment, or participants might fluctuate between search modes across trials. In either case, ambiguities about search strategies can lead to unclear interpretations of an observed P_D component, culminating in false conclusions concerning whether or not salient stimuli capture attention.

Ignoring Salient Distractors via Selection History
by Heleen A. Slagter, Dirk van Moorselaar, and Anna Schubö

The ability to prevent attentional capture has been shown to critically depend on learning of distractor regularities as well as on short-term influences from recent experience, both thought to be implicit and inflexible (often collectively

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[3] Three general points are worth making about the strategies described here. First, these might be selected consciously and deliberately by participants. But it is also possible that these strategies, including those that change as the result of experience, are neither conscious nor deliberate. Second, in the context of visual search tasks, it may sometimes be possible to change strategies "on the fly," in response to a preliminary assessment of a display (e.g., Zohary & Hochstein, 1989). However, the weight of evidence suggests that strategies have some "inertia": they tend to persist over time and are not easily switched on a trial-by-trial basis (e.g., Leber & Egeth, 2006). Third, a selected strategy may not be optimal for a given display, because there is a trade-off between cognitive effort and efficacy (e.g., Irons & Leber, 2016). These points notwithstanding, the choice of search strategy adopted by observers, whether deliberate or not, and whether optimal or not, can greatly influence the distractibility of salient stimuli.

referred to as *selection history*; Chelazzi et al., 2019; Noonan et al., 2018; Slagter & van Moorselaar, 2021; Theeuwes et al., 2022; van Moorselaar & Slagter, 2020). Several studies have shown that observers can learn to ignore salient distractors based upon their prior features (e.g., Vatterott & Vecera, 2012; Stilwell et al., 2019; Gaspelin & Luck, 2018a), prior locations (e.g., Failing et al., 2019; Ferrante et al., 2018; Noonan et al., 2016; Sauter et al., 2018; Wang & Theeuwes, 2018a, 2018b), and the probability of their presence (Geyer et al., 2008; Moher et al., 2011; Won & Geng, 2018, 2020). Furthermore, many studies showing suppression of salient distractors used experimental designs in which the color of the singleton distractor was fixed across trials (e.g., Gaspelin & Luck, 2018b). These findings are consistent with the notion that selection history may play a key role in eliminating attentional capture (Luck et al., 2021).

Statistical learning of distractor features and locations—and the corresponding reduction in capture—has been associated with an "early" P_D component (e.g., 100–200 ms) that occurs before the typical N2pc time window. For example, Wang et al. (2019) found that salient color singletons elicited a P_D emerging around 100-ms when these distractors appeared at a high-probability location, a finding that was presumed to reflect suppression of the distractor as a result of implicit learning. To further explore how learning shapes the time course of distractor suppression, van Moorselaar and colleagues (2021) compared distractor processing in a condition without any regularity to conditions where participants could learn to predict the upcoming distractor's location, its features (i.e., shape and color), or both. They found that both feature and location learning shifted the onset of the P_D earlier in time than in the baseline condition. Thus, statistical regularities of distractors across trials, whether spatial or feature-based, seem to facilitate suppression of distractors in order to prevent attentional capture.

Interestingly, some studies have also reported a learning-based reduction in amplitude of a "late" P_D (250–350 ms) that occurred after an initial N2pc. This has mostly occurred in search tasks in which the target and distractors were defined on the same feature dimension (e.g., van Moorselaar et al., 2020; van Moorselaar & Slagter, 2019). These findings suggest that when salient distractors are

difficult to distinguish from the target stimulus, statistical learning may only influence reactive suppression after initial capture. When the distinction is easy (e.g., when the salient distractor is defined by color and the target is defined by shape), statistical learning may allow participants to proactively suppress the salient distractor to prevent attentional capture (see also the section on the "Dimension Weighting Account").

Learning of distractor regularities necessarily involves repetition. For example, if a salient distractor appears at a given location with a high probability, there will necessarily be many trials in which the salient distractor repeats its location from the previous trial. This is important because several studies have shown that the location and feature of search items from the previous trial can automatically influence attentional allocation (called *intertrial priming*; Maljkovic & Nakayama, 1994, 1996; Talcott & Gaspelin, 2020; see review by Lamy & Kristjansson, 2013). Yet, to date there is little evidence that intertrial priming modulates the P_D component. For example, Feldmann-Wüstefeld and Schubö (2016) examined the effect of distractor-color repetition when the distractor's color varied unpredictably or alternated in triplet sequences. They reported no distractor-elicited P_D component in any of the conditions, suggesting that 3 distractor-color repetitions do not suffice to elicit a P_D component. Moreover, van Moorselaar and colleagues (2021) tracked the emergence of the early P_D in a statistical learning study and found a P_D only after 20 feature repetitions. It thus appears that the modulation of the P_D reflects learning across longer time scales and may not be due to intertrial priming, per se, but future research is necessary to establish how much learning is necessary to modulate the P_D.

Interestingly, the experimental task on the previous trial does strongly affect distractor suppression as evidenced by the P_D component. For example, Feldmann-Wüstefeld and colleagues (2015) had participants perform a categorization task that was randomly intermixed with a search task. When the categorization task involved categorizing a color singleton as blue or green, the attentional priority of color transferred to a red singleton in a search task on subsequent trials: The salient distractor captured attention (as evidenced by an N2pc) before it was suppressed (as indicated

by a subsequent P_D). When the categorization task involved classifying a shape singleton (hexagon vs. triangle), however, the same color singleton did not capture attention (i.e., it elicited a P_D with no N2pc). Later studies suggested that this effect of selection history could not be overcome by explicit cueing of the upcoming trial type, and required almost 200 trials for extinction, indicating that the bias resulted from prior selection episodes rather than the observer's intention (Feldmann-Wüstefeld et al., 2015; Kadel et al., 2017; see also Berggren & Eimer, 2016). However, the attention bias could be reduced by using either a variant of the paradigm that encouraged voluntary choice on the next trial (Henare et al., 2020), or by making the task sequence perfectly predictable (Abbasi et al., 2023). Both manipulations eliminated attentional capture (no N2pc), while a P_D was still observed.

In sum, it is clear that selection history can influence the magnitude, presence, and latency of the P_D component. These findings are generally consistent with the interpretation that the P_D component measures a suppressive process, and that the ability to ignore distractors becomes stronger as participants gain experience with them.

The Dimension Weighting Account
by Heinrich R. Liesefeld and Ananya Mandal

One theoretical approach to explain how stimulus-, goal-, and experience-driven influences combine—and that also acknowledges a specific function for signal suppression indexed by the P_D—is the *dimension weighting account* (DWA; Found & Müller, 1996; Müller et al., 1995). According to the DWA, experience and task goals modulate how strongly salience signals from various feature dimensions affect visual search. Specifically, attentional weights can be adjusted at the processing stage where (feature-less, but dimension-specific) salience signals are integrated into a search-guiding priority map. For example, a slightly tilted bar among vertical bars by itself exerts only little stimulus-driven guidance due to its weak salience, but its salience signal might be amplified because the observer looks for tilted bars (goal-driven) or because the previous search target was a tilted bar (experience-driven). From this perspective, distractor handling starts before the onset of a search display, either by increasing the weights for salience signals from the target dimension or by reducing the weights for those

from the distractor dimension. The DWA has been supported by a wide variety of studies using psychophysics, mental chronometry, computational modeling, eye tracking, EEG, and fMRI (see reviews by Krummenacher & Müller, 2012; Liesefeld et al., 2018).

One recent line of evidence for the DWA that is relevant to the current paper has come from studies using a version of the additional singleton paradigm that allows precise control over the stimuli's salience. In these studies, participants look for a pop-out target (e.g., a 12° tilted bar in a large array of homogenously oriented vertical bars) and a salient distractor is present on some trials. Critically, two types of distractors are typically used: same-dimension and different-dimension distractors. A *same-dimension distractor* is a distractor that is salient in the same dimension as the target (e.g., a bar tilted 45° in the opposite direction than the 12° target). Because any advance downweighting of salience signals from the distractor dimension would also reduce target priority and vice versa (because observers can only down-weight salience signals rather than specific feature values), the DWA predicts that such a target/distractor combination cannot be differentially weighted in advance. Consequently, if the same-dimension distractor is more salient than the target, it initially obtains a higher value on the priority map and will therefore reliably capture attention. Confirming these predictions, this design produced the clearest electrophysiological evidence for attentional capture (see Liesefeld & Müller, 2019): the same-dimension distractor elicited an N2pc that occurred before the target N2pc and the target-elicited N2pc was delayed by distractor presence, suggesting that the distractor captured attention and delayed the allocation of attention to the target (Liesefeld et al., 2017). Of special importance here is that following the distractor-elicited N2pc, a P_D component emerged (Figure 7A). This pattern of results is indicative of reactive control (Braver, 2012; Geng, 2014), with the P_D potentially indexing a suppressive process involved in recovery from capture, such as disengagement of attention (Fukuda & Vogel, 2009, 2011; Sawaki et al., 2012) and/or avoidance of revisiting the distractor (*inhibition of return*, Klein, 2000; e.g., as implemented in the computational model of Moran et al., 2013, which
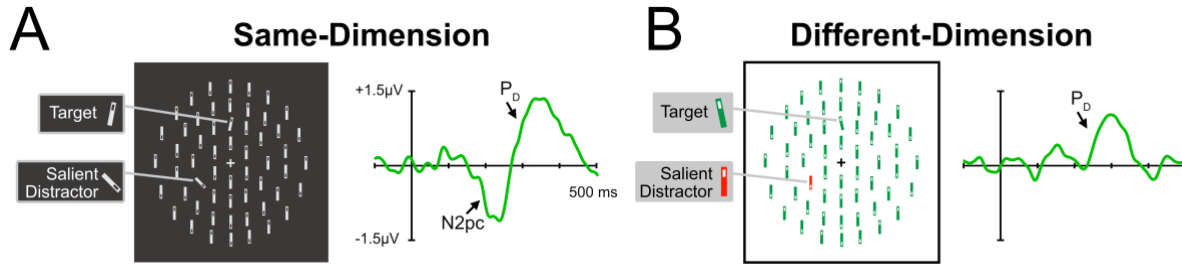
Figure 7. Stimuli and results supporting the dimension weighting account. from (A) Liesefeld et al. (2017) demonstrated that same-dimension distractors elicit an N2pc followed by a P_D component. (B) Liesefeld et al. (2022) demonstrated that a different-dimension distractor in a task design modelsed after Liesefeld et al. (2017) elicited a P_D component with no N2pc.

has been adapted to the additional-singleton - paradigm by Liesefeld & Müller, 2021).

Other conditions of these studies used *different-dimension distractors* in which the salient distractor was defined in a different dimension than the target (e.g., a color-singleton distractor and an orientation target). It is clear from these studies that different-dimension distractors are heavily downweighted. First, different-dimension distractors interfere less with behavioral search performance than same-dimension distractors (Liesefeld et al., 2019). Second, instead of producing an N2pc followed by a P_D (as evoked by same-dimension distractors and indicative of capture), different-dimension distractors elicit only a P_D in an otherwise identical experimental setup (Figure 7B; Liesefeld et al., 2022).

It is intriguing that in some previous studies distractors reliably produced residual interference effects, even when they were salient in a different dimension than the target (e.g., Theeuwes, 1992; see Figure 4A). This might indicate that the salience signals are never fully eliminated (i.e., dimensional weights are never brought to zero), so that a different-dimension distractor will typically cause some residual activation on the priority map (at least when search is salience-based; see also the section on "Search Strategy: Feature-Search and Singleton-Detection Mode"). Liesefeld et al. (2022) speculated that in studies in which distractors are salient in a different dimension than the target, as in the large majority of studies reporting a P_D during pop-out search (e.g., Burra & Kerzel, 2013; Jannati et al., 2013), the P_D reflects a resolution process that is needed to decide between multiple peaks on the priority map. In particular,

only when the residual distractor activation on the priority map is suppressed would attention be free to shift to the stimulus with the highest activation on the map (i.e., the less salient, but dimensionally-upweighted target in these studies). Thus, the cognitive process reflected by the P_D would effectively implement a winner-takes-all mechanism (see Livingstone et al., 2017, for empirical evidence compatible with that idea). In sum, from the DWA perspective, the P_D likely signals a suppressive mechanism akin to the one proposed by the signal suppression hypothesis. However, this suppressive mechanism either serves to give the final impetus for a shift of attention towards the target when the target already has highest priority (e.g., when salience signals from more salient different-dimension distractors are sufficiently downweighted) or to reactively recover from capture when the distractor initially has the highest priority (which inevitably is the case for same-dimension distractors more salient than the target).

Controlling Access to Visual Working Memory
by Heinrich R. Liesefeld and Dominique Lamy

Visual working memory (VWM) is a processing hub that serves ongoing tasks by fulfilling several crucial cognitive functions via the active maintenance of visual information (Liesefeld & Müller, 2019; Luck & Vogel, 1997, 2013). Important for the present purposes, there is now considerable evidence that visuospatial attention may be used to help control what information has access to visual working memory (Vogel et al., 2005). As a result, many models of

VWM now assume that a common spatial priority map coding for potential relevance at each location in the visual field guides both attentional selection and access to VWM (Bundesen, 1990; Liesefeld et al., 2020). Accordingly, manipulations that have well-established effects on search guidance also have strong effects on VWM performance—for instance, highlighting more relevant stimuli via cues (Bays et al., 2011; Emrich et al., 2017), varying stimulus salience (Constant & Liesefeld, 2021, 2023), or introducing statistical regularities (Conn et al., 2020; Umemoto et al., 2010).

Consistent with a strong overlap in underlying control processes, the results from several studies indicate that the mechanism indexed by the P_D does not only play a role in the deployment of attention, but also in encoding into VWM. In particular, Feldmann-Wüstefeld and Vogel (2018) provided a direct demonstration of a link between the P_D and VWM encoding. On each trial, displays contained 2 to-be-memorized stimuli (colored disks, *targets*) accompanied by 2, 4, or 6 to-be-ignored stimuli (colored squares, *distractors*). Adapting a method from the attentional capture literature (e.g., Hickey et al., 2009), they presented either of the two stimulus types on the vertical midline, while the other type was presented on the horizontal midline. The crucial finding was that the lateralized distractors elicited a P_D component, suggesting that they were suppressed to avoid their encoding into VWM. Importantly, this P_D component's amplitude increased with 4 relative to 2 distractors and did not increase further with 6 distractors. This finding indicates that the mechanism indexed by the P_D is sensitive to the amount of suppression required and may have a fixed, limited capacity. Finally, P_D amplitude showed a positive correlation with general VWM performance, a result that nicely dovetails with earlier observations that P_D amplitude measured in an additional-singleton paradigm correlates with VWM performance (Gaspar et al., 2016).

Other studies further suggest that the P_D may specifically index a process involved in filtering out irrelevant information by preventing its encoding into VWM. Liesefeld et al. (2014) cued participants to attend to either the left or the right hemifield and memorize a variable number of targets amongst a variable number of distractors for subsequent change detection. They found that the to-be-ignored distractors elicited a positivity at the same electrode sites and in the same time range as previous studies of the P_D, which is consistent with the idea that participants were suppressing irrelevant distractors to better recall target stimuli. The latency of this P_D-like component was negatively correlated both with VWM performance (in line with the above-mentioned correlations reported by Feldmann-Wüstefeld & Vogel, 2018; Gaspar et al., 2016) and with the amplitude of a pre-frontal signal, with both indices showing a close association with the effect of distractor presence on maintenance-related parietal delay activity. The authors concluded that detection of distractors in posterior brain regions, indexed by the P_D-like component, triggers a prefrontal bias signal that reduces the amount of distractor information encoded in VWM (see also Emrich & Busseri, 2015).

A recent study by Hakim et al. (2021) provided additional evidence for the idea that the P_D indexes processes that control access of spatially attended information into VWM. The authors presented intervening stimuli during the retention interval of a VWM task (either irrelevant distractors or stimuli labeled "task-relevant distractors" that were associated with an additional go/no-go task). They relied on the P_D as a measure of distractor suppression, on contralateral delay activity (CDA; e.g., Luria et al., 2016; Vogel & Machizawa, 2004) as a measure of encoding into VWM, and on lateralized alpha power as a measure of spatial attention allocation (e.g., Foster & Awh, 2019; Peylo et al., 2021; but see Balestrieri et al., 2022 for an alternate interpretation of alpha-band lateralization). The main conclusion of this study was that both relevant and irrelevant distractors captured visuospatial attention, but unlike the former, the latter were suppressed (i.e., triggered a P_D) and were not encoded into VWM.

Taken together, these findings suggest that the efficiency of distractor filtering—as indexed by the P_D component—is of crucial relevance for controlling access to VWM and that interindividual differences in this ability are related to VWM performance (see also Awh & Vogel, 2008; Vogel et al., 2005). Thus, the P_D is highly relevant for basic and applied research, because the mechanisms it indexes have a much more profound and long-lasting impact on human cognition than via fleeting attention allocations alone (see also Constant & Liesefeld, 2023).
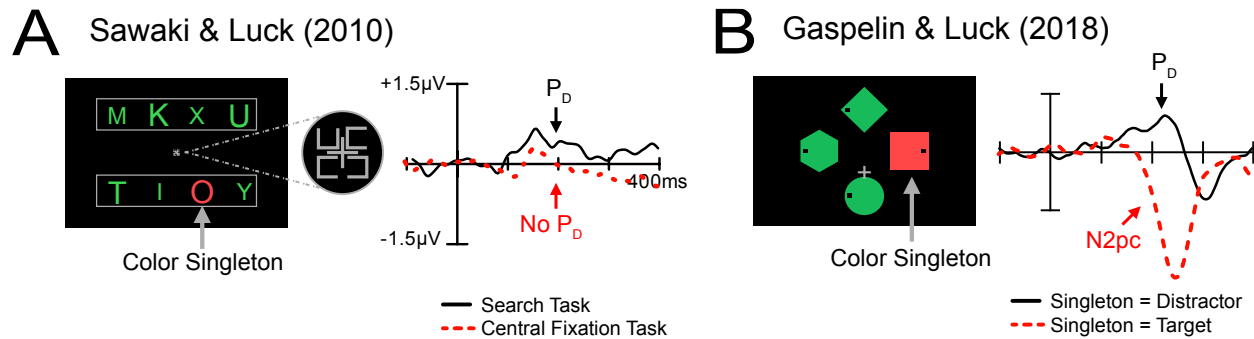
Figure 8. Two approaches for ruling out sensory-level ERP components. (A) Sawaki and Luck (2010, Exp. 3) had participants perform a central fixation task, which eliminated the P_D component from the original search task. (B) Gaspelin and Luck (2018, Exp. 3) made the singleton a distractor in one half of the experiment and a target in the other half. The P_D occurred only when the singleton was a distractor, suggesting it was not a general salience signal. In both panels, ERPs are contra-minus-ipsi difference waveforms.

Ruling Out Sensory Effects
by Nicholas Gaspelin and Dirk Kerzel

The previous sections reviewed evidence that the P_D component indicates a suppressive process that is applied to salient distractors to prevent attentional capture. However, not all lateralized positivities in visually evoked ERPs are necessarily a P_D component. A lateralized positivity could instead arise from low-level imbalances in "sensory energy" caused by presenting a feature singleton in one hemifield but not the other. For example, this could cause a Ppc component indicating a generalized salience signal (Barras & Kerzel, 2016, 2017; Corriveau et al., 2012). It could also cause a larger contralateral P1 waveform owing to feature-specific lateral inhibition (Schein & Desimone, 1990) or lower levels of adaptation for the singleton's feature (Luck & Hillyard, 1994a, 1994b). Such sensory-level ERP components could easily be confused with the P_D component. It is therefore worth discussing what these components are and how they can be disambiguated from a P_D component.

One specific component of concern is the *positivity posterior contralateral (Ppc)* component, which is a positive-going deflection that occurs in posterior electrodes sites (e.g., PO7/PO8) contralateral to a salient stimulus and tends to occur in the time range of 80–150 ms. Importantly, the Ppc component seems to be unrelated to suppression and seems to instead be related to

imbalances in low-level sensory properties of the stimuli across hemifields. For example, Corriveau et al. (2012) had participants search displays of gray circles for a color singleton target in one color (e.g., a red circle) and ignore a color singleton in another color (e.g., green circle). There was a positive-going deflection at electrode sites contralateral to the singletons that occurred irrespective of whether the singleton was a target or distractor. Because the target should not be suppressed, the authors concluded that this lateralized positivity was not a P_D component. Instead, they suggested this Ppc component reflected a salience signal generated by the color singleton (see also Barras & Kerzel, 2016, 2017; Fortier-Gauthier et al., 2012; Leblanc et al., 2008). Consistent with this idea, early positivities are sometimes reduced when the distractor is less salient (Drisdelle et al., 2023; Kerzel & Huynh Cong, 2022). Relatedly, the positivity could have also indicated a kind of P1 adaptation effect, whereby the visual system adapted more to gray neutral distractors (of which there were eight in each display) than to color singletons (of which there were only two in each display). In either case, the Ppc component would be caused by low-level sensory properties that are unrelated to attentional

suppression.[4]

Some initial studies of the P_D component used control experiments to rule out low-level sensory effects. For example, recall that Sawaki and Luck (2010) had participants search for a target letter while ignoring a color singleton and that the color singleton elicited a P_D component (black line in Figure 8A). To test whether this P_D was due to low-level sensory effects, they used a *central fixation control task*, which used the same stimuli as the search task, but participants searched a small display of Landolt C's centered at fixation for an stimulus with a specific orientation (e.g., upward C). This central fixation task should focus visuospatial attention at the center of the display, reducing the need to suppress the salient distractor in the periphery. If the P_D in the search task was actually due to a low-level sensory effect (e.g., a Ppc), the lateralized positivity should appear even when attention is focused at fixation. If the lateralized positivity disappears, however, then it suggests that the previously observed positivity was not due to a low-level sensory effect and instead reflects something about attentional suppression. As can be seen, the P_D was eliminated in the central fixation task, ruling out a low-level sensory effect (see also Donohue et al., 2018, Exp. 3).

Another approach is to use a *singleton-target control task* (Figure 8B). For example, Gaspelin and Luck (2018b) found that a color singleton elicited a P_D component, which they attributed to suppression. To rule out the possibility of a salience signal, they ran a control experiment, suggested by John McDonald, in which the color singleton was the distractor for one half of blocks and was the target for the other half of blocks (similar to Corriveau et al., 2012; Barras & Kerzel, 2017). If the lateralized positivity was due to a low-level sensory effect (e.g., a Ppc), this positivity should occur irrespective of whether the singleton was a target or distractor. In both instances, the singleton should be salient and should therefore generate the low-level sensory effect. If the lateralized positivity was instead due to suppression (i.e., a P_D), this positivity should be eliminated when the color singleton is the target, as the participant cannot suppress the target and still perform the task. Consistent with the latter interpretation, the P_D component was eliminated when the singleton was a target, suggesting it was specifically involved in some process related to rejection of a salient distractor.

In sum, some lateralized positivities may be due to low-level sensory imbalances caused by presenting salient distractors in one hemifield, and these could easily be confused with a P_D component. These sensory components occur mostly early (between 80–150 ms post-stimulus) and have been referred to as Ppc. A hallmark of the Ppc is that it does not differ between target and distractor stimuli, whereas the P_D does. Thus, to make sure that a positivity does indeed reflect suppression, it is important to conduct control experiments that rule out the possibility of a low-level sensory effect.

Alternative Accounts
by Matthias M. Müller and Dirk Kerzel

Many of the previous sections presented evidence supporting the idea that the P_D component reflects suppression of salient distractors. However, there are alternative accounts of this component. It should be noted that the N2pc and the P_D are calculated by subtracting ipsilateral from contralateral voltages. These difference values might cause some ambiguity because the N2pc and P_D occur in similar time ranges at the same electrodes. As explained above, a P_D to a distractor corresponds to a more positive voltage contralateral to the hemifield containing the distractor. However, it is possible to re-interpret this difference relative to the other hemifield. That is, a more positive voltage contralateral to the distractor can also be viewed as a more negative voltage contralateral to the hemifield without

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[4] Although the majority of studies reported an early positivity when the search display contained a sensory imbalance, it should be noted that some studies reported the opposite. For instance, Forschack et al. (2022b) and Donohue et al. (2018) observed a negativity in the interval of the Ppc, which they referred to as N1pc. This N1pc was purported to reflect some early attentional process. It is puzzling that their stimuli and tasks were similar to the studies by Gaspelin and Luck (2018b), Kerzel and Burra (2020), and Corriveau et al. (2012), respectively, yet the early ERPs were opposite. While an early negativity is unlikely to be confused with the P_D, further research is required to resolve these apparent contradictions.
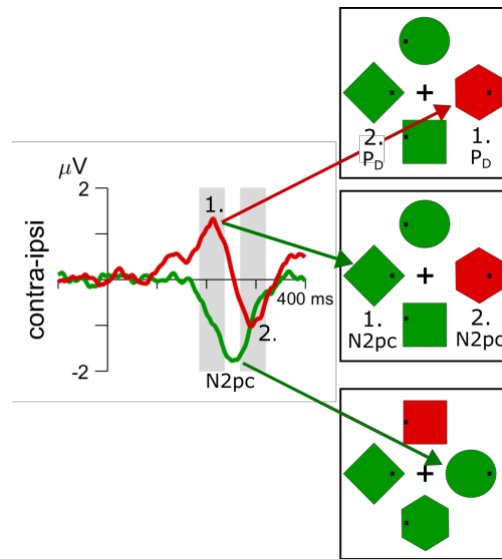
Figure 9. ERPs to lateralized stimuli in a feature search task where the target was a circle, and the distractor was red. The data is from Experiment 2 in Kerzel and Burra (2020). Time zero marks the onset of the search display. When the target was presented at a lateral position, an N2pc occurred (green line). When the salient distractor was shown at a lateral position, the polarity of the ERP flipped (red line). Two divergent interpretations of the flip are shown in the top panels. The elicited ERP components are numbered in the order in which they are purported to occur (1 and 2). According to Kerzel and Burra (2020; middle panel), the target-colored distractor is first attended (resulting in the first N2pc) and the salient distractor is attended second (resulting in the second N2pc). According to Drisdelle and Eimer (2021; top panel), the salient distractor is suppressed first (resulting in the first P_D), and the target-colored distractor is suppressed second (resulting in the second P_D).

distractor. Thus, a P_D to a distractor in one hemifield is equivalent to an N2pc to a stimulus in the hemifield without distractor.

The recent controversy around distractor-elicited potentials in feature-search mode with small search displays illustrates this ambiguity (see Figure 9). Gaspelin and Luck (2018b) observed a P_D to the distractor, suggesting that this distractor was attentionally suppressed. Consistently, search times were shorter when the distractor was present, as if suppression had reduced the effective set size from four to three stimuli. Kerzel and Burra (2020) replicated the study by Gaspelin and Luck (2018b) and observed that the positivity to the distractor was followed by a negativity (a so-called *P-N flip*). While observed in several studies (Drisdelle & Eimer, 2021; Gaspelin & Luck, 2018b, Exp. 3; Stilwell et al., 2022, Exp. 1), the P-N flip has been interpreted in different ways. Kerzel and Burra (2020) suggested that the P-N flip was a sequence of two N2pc's and reflected an idiosyncratic scanning strategy that occurs with small set sizes. Because the salient distractor's color was

predictable, participants may have created a template for rejection (Arita et al., 2012) and directed attention away from the salient distractor. Thus, the initial P_D to the distractor was reinterpreted as an N2pc elicited by the inconspicuous nontarget on the opposite side, whereas the subsequent negativity was seen as an N2pc to the distractor, which was selected despite being irrelevant. The idea of sequential selection of lateral stimuli was supported by shorter RTs for horizontal than for vertical targets. According to this account, then, the apparent P_D reflects upweighting of a nontarget rather than downweighting of the salient distractor (see also Kerzel & Hyunh Cong, in press). Consistent with this possibility, recent evidence suggests that the P_D is attenuated when target features are no longer fixed but instead vary randomly (van Moorselaar et al., 2023): in that case, nontargets contralateral to the distractor no longer benefit from upweighting of the target color. However, in that study the P_D was not eliminated, suggesting that both upweighting of the majority color and

downweighting of the salient distractor's color can occur concomitantly (see Chang & Egeth, 2019, for additional evidence).

There has been some evidence against the idea that the P_D reflects attentional allocation to the nonsingleton distractor on the horizontal midline. For example, Drisdelle and Eimer (2021) discouraged any horizontal attentional scanning strategy by ensuring that the target *never* appeared at lateral positions, yet the P-N flip persisted. The authors concluded that the P-N flip might reflect an initial P_D to the singleton distractor followed by a P_D to the nonsingleton distractor. In addition, Stilwell et al. (2022) also showed that the P_D occurred even at high set sizes in which an idiosyncratic search strategy should be discouraged (see also Drisdelle & Eimer, 2023; Gaspar & McDonald, 2014; Sawaki & Luck, 2010). Finally, Tam et al. (2022) applied a computational model of attention to simulate the P-N flip and found the P-N flip occurred even in a model where the salient distractor was suppressed to baseline (while the nonsingleton distractors were first activated and then suppressed below baseline). However, the conclusions from this study also critically depend on the interpretation of the components as a P_D elicited by a distractor on one side or as an N2pc to a distractor on the other side. To conclude, there is no definitive answer as to what processes the P-N flip might index and further research is therefore needed to answer this question.

In an attempt to resolve the ambiguity between the N2pc and P_D components in ERP studies of distractor suppression, several studies have relied on other measures of stimulus enhancement and inhibition, namely, steady state visual evoked potential (SSVEPs) and alpha-band oscillations. The SSVEP is an oscillatory electrophysiological response of the visual cortex to a flickering stimulus. The frequency of the SSVEP matches the frequency of the flickering stimulus and previous research has established that its amplitude increases when a stimulus is attended (Morgan et al., 1996; Müller et al., 2003; Norcia et al., 2015). Alpha oscillations are not locked to the frequency of the stimulus, but occur in a fixed frequency range of 8–12 Hz and their amplitude was found to decrease in the hemisphere contralateral to the attended stimulus (Thut et al., 2006). Thus, SSVEPs and alpha oscillations

measure the deployment of attention in different ways.

To measure SSVEPs, it is necessary to use flickering search displays rather than the typical abrupt-onset search displays. Accordingly, several SSVEP studies presented each search display as a brief change in color and shape within an ongoing stream of flickering grey disks, with the critical stimuli placed on the horizontal and vertical meridian, as in previous studies on the P_D. As shown in Figure 10A, the typical P_D component was observed when the target was vertical and the distractor was lateral (DLTV), both with 4-item displays (Forschack et al., 2022a) and with 2-item displays (Forschack et al., 2022b). If the observed P_D indicates attentional suppression of the distractor, the amplitude of the SSVEP corresponding to the distractor frequency should decrease after search display onset and the amplitude of alpha oscillations contralateral to the distractor should increase. However, the opposite pattern of results was observed as is clear from Figures 10B and 10C. Thus, frequency-based measures of attentional deployment suggest that participants were attending the distractor, rather than suppressing it.

Given these results, frequency-based measures of attentional deployment are inconsistent with the idea that the P_D is an index of proactive attentional suppression. A similar inconsistency was reported with regard to findings by Hilimire et al. (2012) and Kiss et al. (2012). These authors found that the P_D to the distractor was larger when the distractor was shown together with a target than when it was presented alone and concluded that the P_D reflects distractor suppression in the service of target disambiguation. However, Forschack, Gundlach, et al. (2022a) and Forschack, Gundlach, Hillyard and Müller (2022) failed to replicate this effect: they found a larger P_D when the distractor was shown alone. In addition, SSVEP amplitudes at the frequency of the lone distractor were increased relative to the pre-cue baseline, suggesting that it was attended.

Finally, attentional suppression is expected to increase with the saliency of the distractor (Stilwell et al., 2023; but see Ramgir & Lamy, in press; Wang & Theeuwes, 2020). The reason is that target saliency facilitates attentional selection. Therefore, more suppression is expected to prevent the potentially stronger attentional capture by more
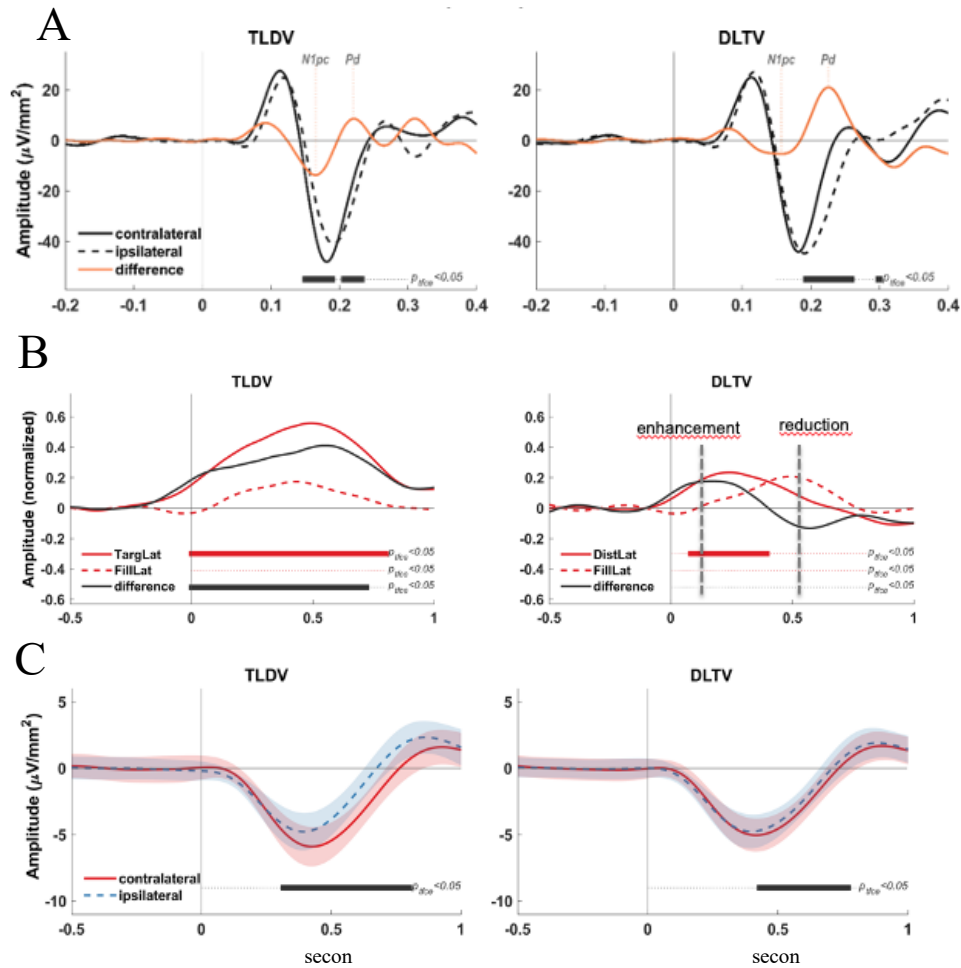
Figure 9. Data from Forschack, Gundlach, et al. (2022a). Time zero marks the onset of the search display. (A) Grand mean current source densities at electrodes PO8 and PO7 contra- and ipsilateral to the lateral target (with distractor vertical, TLDV) or to the lateral distractor (with vertical target, DLTV). The difference potential between contralateral and ipsilateral electrodes is shown in orange. The black horizontal bars indicate significant difference potentials. (B) Grand mean SSVEPs for lateral target, distractor, and non-target stimuli ("fillers" = Fill). The red horizontal bars indicate significant differences with respect to the baseline before search display onset. Significant differences between target/distractor and inconspicuous "filler" stimuli are indicated by the black horizontal bar. (C) Grand mean contra- and ipsilateral alpha-band activity. Shaded areas indicate 95% confidence intervals relative to pre-stimulus baseline. The black horizontal bars indicate significant differences between contralateral and ipsilateral amplitudes (i.e., alpha-band lateralization).

salient distractors. However, Forschack and colleagues (2023) found that the distractor-elicited P_D was unaffected by distractor saliency. Similarly, the contralateral alpha amplitude was unaffected. In contrast, target selection was indeed facilitated by increased salience, as evidenced by an earlier N2pc to the target and shorter RTs (Töllner et al., 2011). Thus, the predicted increase of attentional suppression with increased distractor saliency was not observed. It should be noted, however, that

other studies have found the P_D to increase in magnitude with distractor saliency (Drisdelle & Eimer, 2023; Gaspar & McDonald, 2014). Thus, future research is needed to resolve this apparent discrepancy.

In sum, the findings from typical ERP studies of the P_D and from studies using frequency-dependent measures do not converge. While the former link the P_D to suppression of the salient distractor, the latter report a P_D together with

evidence showing that the distractor is attended rather than suppressed, namely, increased steady-state visual evoked potential amplitudes and decreased contralateral alpha-band amplitudes. Possibly, the enhanced distractor processing is related to one of the following processes, notably (1) the reactive disengagement of attention from the distractor location (Belopolsky et al., 2010; Klink et al., 2023; Theeuwes, 2010), (2) the "zooming in" on the target while ignoring the distractor (Forschack et al., 2022a, 2022b; Liesefeld et al., 2021), (3) the learning of task-irrelevant features (van Moorselaar & Slagter, 2019), (4) the shielding of working memory from highly distracting input (Feldmann-Wustefeld & Vogel, 2019), or (5) the redirecting of attention away from salient distractors (Kerzel & Burra, 2020). In other words, more research is needed to bridge the gap between these studies. In particular, whether the results from frequency-based measures generalize to different sets of stimuli and tasks would be an important next step in this endeavor.

Application to Clinical Science
by Nicholas Gaspelin

The P_D component could be used as a translational tool to study mental health disorders that involve dysregulations of inhibition and cognitive control. One line of evidence for this has come from studies of individuals with anxiety disorders. For example, Gaspar and McDonald (2018) recently found that individuals with high anxiety had difficulty suppressing salient distractors. High-anxiety individuals showed an initial N2pc followed by a P_D component, whereas low-anxiety individuals showed only a P_D component (i.e., similar to the results in Figure 7, but using different stimulus displays). This finding was taken to indicate that the high-anxiety group had difficulty preemptively suppressing salient distractors to prevent distraction. Additionally, Kappenman and colleagues (2021) had high- and low-anxiety individuals attempt to ignore a stimulus that was previously associated with shock. In both the high- and the low-anxiety groups, the stimulus elicited an N2pc component indicating that it captured attention. Interestingly, individuals with high anxiety had a larger "late" P_D after the initial N2pc than individuals with low anxiety. This finding suggests that suppression may be enhanced in individuals with anxiety disorders, a mechanism

that would presumably help these individuals avoid threatening stimuli after initial distraction.

Distractor suppression may also provide useful tools to understand schizophrenia, a condition that is known to involve attentional impairments (Luck & Gold, 2008). For example, one recent hypothesis is that individuals with schizophrenia may "hyperfocus" their attentional resources, and that, as a result, they have difficulty distributing their attention across space, and show supranormal control over attention (Luck et al., 2019). Interestingly, the extent of such hyperfocus was shown to correlate with impairments in a variety of general cognitive functions. Studies relying on the P_D component played a pivotal role in elaborating this hypothesis. For instance, it was shown that relative to control participants, individuals with schizophrenia were (ironically) better able to ignore task-irrelevant distractors and showed an enhanced P_D component in a typical laboratory tasks to study distractor suppression (Sawaki et al., 2016). Similar results have been found with eye-tracking measures of suppression (Bansal et al., 2021).

In sum, inhibition and cognitive control processes are impaired to some extent in a variety of mental health disorders. It therefore seems likely that the investigation of these disorders could directly benefit from ERP measures of distractor suppression such as the P_D component.

Conclusions
by Nicholas Gaspelin and Dominique Lamy

As reviewed, there has been an abundance of research using the P_D component to study inhibition of distracting stimuli. Some of this research has demonstrated that salient distractors can be suppressed to prevent attentional capture. Other research has shown that, in situations where distraction cannot be prevented, suppression can be used to mitigate the effects of distraction (e.g., via suppression that occurs after the initial shift of attention). Furthermore, much of the evidence from the P_D component has suggested that distractor suppression is learned as participants gain experience with the expected features and locations of salient distractors. Future research is needed to delineate the boundary conditions under which salient distractors can and cannot be ignored.

Although the findings from many studies are consistent with the notion that the P_D component

measures a suppressive attentional process,[5] a few studies have questioned this interpretation, mainly based on findings using steady-state visually evoked potential (SSVEPs) and alpha-band oscillations as measures of attentional allocation, and further research is therefore needed to clarify the discrepancies between these measures and the P_D.

In conclusion, the P_D has been a powerful tool toward understanding how humans handle distraction and promises to be an important ERP component for future research on this topic. In addition to understanding the basic cognitive neuroscience of attention, the P_D component could also help provide insights in translational work in clinical science.

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[5] It is important to note that there is an inherent challenge in establishing the meaning of the P_D component. On the one hand, in order to test the hypothesis that the P_D component reflects suppression, a strong theory is needed which specifies when suppression will and will not occur. On the other hand, if such a theory existed, the P_D component would not be particularly useful as a diagnostic tool of suppression because we would already know when suppression occurs and when it does not. However, this inherent circularity is not specific to the P_D and has challenged ERP research aimed at linking ERP components with specific cognitive processes since its beginnings (for a more detailed discussion of this general issue, see Kappenman & Luck, 2012, pp. 17-20).

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