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Inhibition as a Potential Resolution to the Attentional Capture Debate

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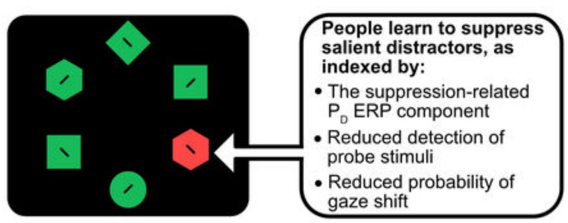
Abstract

Physically salient stimuli, such as uniquely colored objects, seem to have an inherent power to capture our attention, but formal research on this topic has produced conflicting results and theories. Here, we review evidence that the attentional capture debate can be resolved by positing a new suppressive process. This suppressive process can occur before attentional shifting to prevent salient items from attracting attention. In the current article, we review converging evidence that salient items are suppressed to avoid attentional capture comes from studies of psychophysics, eye movements, single-unit recordings, and event-related potentials (ERPs). Crucially, the ability to inhibit salient distractors seems to be learned as participants gain experience with the simple features of the to-be-ignored stimuli.

Graphical abstract



Keywords

visual attention; inhibition; attentional capture; visual search

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Introduction

When we search visual scenes, physically salient items seem to automatically attract our attention, even when they are completely irrelevant to our goals. For this reason, brightly colored signs and flashing lights are commonly used as visual warning signals to alert people to important information. From neon traffic signs to flashing beacons on police cars to fluorescent advertisements in storefront windows, people frequently encounter salient stimuli (see Figure 1). But exactly how these salient stimuli are handled by the visual system has been heatedly disputed.

Traditionally, research on *attentional capture* has been divided into two opposing theoretical positions (see Table 1). Bottom-up theories propose that salient stimuli automatically and inevitably capture attention, independent of our knowledge and goals [1,2]. hese models predict rampant distraction in the real world because the visual system is at the mercy of the most salient item in a scene. Top-down theories, however, propose that salient items have no special influence on attentional allocation unless they match the anticipated features of a search target [3–5] or match previous experience (i.e., *selection history*; see [6,7]). Thus, these models predict a kind of "tunnel vision" – whereby salient warning signals that fall outside of one's attentional template will go unnoticed.

The dispute between these two theoretical positions has now lasted for decades. Both positions are supported by numerous studies, which has led to a theoretical stalemate. Recently, however, several researchers have provided evidence that bottom-up capture can be eliminated by means of top-down inhibitory mechanisms [8–12], providing a potential bridge between bottom-up and top-down theories. The *signal suppression hypothesis* [10,13] proposes that salient items automatically produce a priority signal that attracts attention, consistent with bottom-up theories, but that the salient items can be suppressed prior to capturing attention, consistent with top-down theories. It is important to emphasize that this suppression occurs prior to the initial shift of visual attention (an issue that we will discuss in-depth later in this paper). Because this inhibitory mechanism makes it possible to explain why capture is observed in some experiments and not in others, we believe that it provides a plausible resolution to the debate between bottom-up and top-down theories of attention capture, as well as adding a new dimension to general theories of visual search. Note that the idea that inhibition may play a role in attentional guidance is not new (e.g., [14–17]), but the idea that inhibition plays a role in the attentional capture has recently gained considerable traction.

Much has been learned about the suppression of salient stimuli over the past few years. For example, there is growing evidence that suppression of salient stimuli is not a reactive process that is triggered by a salience signal per se (as originally proposed by [10]). Instead, it seems to be the result of a proactive feature -based attention process that downweights objects containing a to-be-ignored feature value, which must be known in advance ([18–20]; but see [21]). Second, although suppression is top-down (as traditionally defined [22]), it now seems likely that it is a result of recent experience rather than an act of will [23,24]. Indeed, if the to-be-ignored feature value varies from trial to trial and is indicated with a precue, attention is initially attracted to this color [25–27]. However, much is still unknown.

For example, most of the research on inhibition of salient stimuli has focused on *color singletons* (a uniquely colored object amongst homogenously colored search items – as in Figure 1), but it is unclear if all types of physically salient stimuli (especially sudden onsets and other dynamic stimuli) can be suppressed.

In the current article, we will review the recent empirical evidence supporting the idea that salient distractors can be inhibited to prevent attentional capture, discuss how this idea has evolved with new findings, and point to important areas for future research.

Behavioral Evidence for Suppression of Salient Distractors

Using newly developed methods, several recent psychophysical and eye tracking studies have shown that salient distractors can be suppressed. Traditional methods for examining the effects of salient distractors are not well suited for examining suppression, because they provide an aggregate measure of the processing of the entire display and cannot indicate whether an individual item was suppressed. A previously-developed probe method [28] has therefore been adapted to examine the suppression of salient distractors (Figure 2a; [8]). On *search trials*, participants searched for a target shape and ignored a uniquely colored *singleton* distractor. On randomly intermixed *probe trials*, letters appeared briefly at each search location and then disappeared; on these trials, participants had to report as many letters as possible. The key result was that participants were less likely to report the letter at the singleton distractor location than the letters at the nonsingleton distractor locations. This *probe suppression effect* suggests that processing at the singleton location was inhibited, impairing the encoding of the probe letter at that location. Other studies have used eye tracking to separately measure processing for each item in the array (Figure 2b; [9,18]). Under conditions that discouraged attentional capture, gaze was less likely to be directed to a salient singleton distractor than to the average nonsingleton distractor item (an *oculomotor suppression effect*).[1]

Electrophysiological Evidence for Suppression of Salient Distractors

Much of the early evidence that salient items can be suppressed came from studies of the recently discovered P_D (*distractor positivity*) component of the event-related potential (ERP) waveform, which was proposed to reflect the suppression of search items [29]. Several studies have found that the P_D component is elicited by salient distractors that fail to capture attention (see Figure 3; [10,11,30,31]). This led researchers to posit that salient items are actively suppressed. However, the behavioral methods used in these experiments were not designed to determine whether the salient items were actually suppressed or whether they simply failed to generate a salience signal. Thus, the initial ERP evidence was suggestive of suppression but did not provide a link between the electrophysiological effects and behaviorally measured suppression of the salient item.

[1]One key methodological issue, however, is that it is difficult to distinguish between upweighting of the target features and downweighting of salient distractor features (for more on this issue, see [13]). More research is needed to fully resolve this issue, but the most straightforward explanation of the above results is that the salient feature was suppressed – especially if upweighting models are constrained to assume that the attentional template is closely tuned to the target feature (but see [5,61]).

A recent study has “connected the dots” between the P_D component and behaviorally-measured suppression [12]. Participants searched for a target shape while attempting to ignore a salient distractor, and a probe method [8] was used to provide a behavioral measure of suppression. The salient distractors elicited both a P_D component and behavioral suppression, and the amplitude of the P_D component was correlated with the magnitude of the behavioral suppression effect.This provides a crucial link between behavioral and electrophysiological measures of suppression.

An alternative explanation of the P_D component is that it reflects the saliency signal produced by the salient distractor rather than suppression of the distractor ([32,33]; but see [29]). This possibility was ruled out in an experiment in which the salient item was the target in one condition and a distractor in another condition (see bottom panel of Figure 3). The salient item elicited a P_D component when it was a distractor (and should be ignored), but not when it was the target (and should be attended) [12]. Thus, the P_D component specifically indexes a cognitive process involved in distractor rejection and does not reflect an automatic salience detection process.

Other evidence that the P_D component is closely tied to distractor rejection comes from a study that concurrently measured eye movements and ERPs [34]. In this study, a salient distractor elicited a P_D component on trials where eye movements were successfully directed to the target (and away from the distractor). However, the P_D component was absent on trials where eye movements were directed to the distractor (i.e., the distract or captured attention). There was also evidence that the magnitude of saccadic curvature from the salient item correlated with the magnitude of the observed P_D component.

Studies of visual working memory have also provided evidence that the P_D component measures distractor suppression. Typically, it is assumed that selective attention is used to control the transfer of perceptual representations into visual working memory, and individual differences in attentional selectivity are partly responsible for individual differences in working memory performance. Specifically, individuals who have low working memory spans seem to encode task-irrelevant information in working memory, whereas those with high working memory spans only encode task-relevant information [35]. Interestingly, individual differences in working memory span were found to correlate highly with differences in P_D amplitude elicited in a separate visual search task [36]. In other words, the ability to filter out irrelevant information is correlated with working memory capacity. Also, in visual working memory tasks, the P_D component is elicited by to-be-ignored memory items and grows incrementally as the number of to-be-ignored memory items is increased [37].

Another key piece of evidence that the P_D component indexes inhibition of salient items comes from a study of macaque monkeys who performed an attentional capture task with concurrent single-unit recordings in prefrontal cortex [38]. When monkeys successfully ignored salient distractors, firing rates were below baseline levels in neurons that represented the salient distractor, indicating that this item was suppressed (see also [39]). Crucially, surface-level recordings over extrastriate cortex yielded a monkey homolog of the P_D

component to the salient distractor. No single-unit suppression effect and no PD component were observed in a monkey who could not learn to suppress the salient distractor.

Inhibition of Salient Items: Not Only Reactive

The empirical studies in the prior sections clearly suggest that salient items can be *proactively inhibited* – inhibition is set up prior to stimulus onset, preventing attentional allocation to the salient item. However, some researchers have argued that search items can be ignored only after they attract an initial shift of visual attention. For example, the *search-and-destroy* hypothesis proposes that to-be-ignored items must first be attended before they are inhibited [26]. Similarly, the *rapid disengagement* hypothesis proposes that spatial attention always moves to the most salient item first, and then top-down processing can be used to direct attention away from this item [2,40]. These models, which propose that inhibition can occur only as a reactive process after attentional allocation, are supported by studies of manual RT ([26,41]; but see [42]), eye tracking experiments [25,43], and some ERP studies ([44]; but see [30]).

It is important to highlight that many studies demonstrating proactive inhibition of salient items directly ruled out reactive inhibition. For example, when the probe paradigm shown in Figure 2a is used, suppression is observed even if the probe letters appear simultaneously with the search display and are masked after 100 ms [8]. This should not have provided sufficient time to direct attention to the salient item and then redirect visual attention to the target. The above-described eye tracking studies were also inconsistent with a pure reactive inhibition model [9], because even the fastest eye movements were biased away from the salient items (see also [39]). Most ERP studies are also inconsistent with pure reactive inhibition: If salient items captured attention before they were suppressed, the suppression-related P_D component should have been preceded by an N2pc component (an index of that allocation of attention to an item). However, most ERP studies of attentional suppression find no N2pc component prior to the P_D component [10–12,34]. Moreover, the P_D component is sometimes observed so early that a prior shift of attention is implausible [10,12,34]. One could always argue that there was some ultrafast, unobservable attentional shift in these studies, but such a theoretical position can easily become unfalsifiable [45]. The data from these studies straightforwardly suggests that salient items can be suppressed without first capturing attention, at least under certain conditions.

To some readers, it may seem that proactive inhibition is implausible *prima facie* and that suppression must always be reactive. After all, how can you ignore something without first attending it? The answer to this question is actually quite simple. For the past 30 years, most models of visual search have proposed that attention can be proactively guided toward task relevant features [46–48]. Prior to stimulus onset, the gain of feedforward connections is modulated so that search items containing the relevant features automatically produce larger attentional priority signals. he gain of attentional priority signals could be modulated by preattentive feature maps [46–48], although this could also be accomplished via some other cognitive mechanism [49,50]. If proactive control signals can be used to increase the processing of items that contain to-be-attended feature values, then it takes little effort to imagine how proactive control signals could also be used to suppress the processing of items that contain to-be-ignored feature values. That is, by reducing the gain for specific feature values prior to stimulus onset, it is possible to effectively reduce the processing of items containing those feature values without first shifting attention toward these items. Consistent with this hypothesis, suppression is typically observed only if the participant knows the features of the to-be-suppressed distractor in advance ([18,19]; but see [51]).

At this point, it should be clear that proactive inhibition of salient items is theoretically plausible and that there is empirical data that straightforwardly suggests that salient items can be proactively suppressed. Why, then, do some studies find that to-be-ignored search items must first be attended before they are inhibited? An important hint comes from a consistent difference in experimental design between these two sets of studies. In most studies demonstrating mandatory reactive inhibition, the to-be-ignored feature value varied from trial to trial and was cued before the search display appeared [25,26,41], whereas in most studies demonstrating proactive inhibition, the to-be-ignored feature was held constant for a long block of trials [8–12].

We hypothesize that proactive suppression of a salient distractor cannot be achieved directly by an act of will and is instead the result of multiple trials of experience with the to-be-ignored feature value [23,24]. When an observer stores a feature value in working memory with the intention of suppressing items containing that feature (e.g., as the result of trial-by-trial cuing of the to-be-ignored feature value), attention is initially captured by that feature, followed by reactive inhibition – attention must shift to the to-be-ignored item before it can be suppressed [25] However, once this feature has been repeated multiple times, proactive inhibition of this feature value builds up, allowing items containing that feature to be avoided. Simply put, proactive inhibition likely results from an automatic, implicit learning process that is a function of recent experience (i.e., selection history). Recent experimental evidence is consistent with this conjecture [18,19,27,52–55,51,56–60], but more research is needed.

Conclusion

Researchers have long debated whether salient items can automatically capture visual attention, but we believe that this issue is now nearly resolved. Converging evidence from ERPs, psychophysics, and eye tracking indicates that people can proactively inhibit salient items to prevent visual distraction. However, this ability appears to build up gradually as participants gain experience with the specific features of the to-be-ignored items.

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Highlights

- A simple suppressive mechanism could resolve the attentional capture debate
- Distractors with known features can be preemptively inhibited to prevent capture
- Suppression is triggered by recent experience rather than an act of will
- Suppression can be observed in psychophysics, eye movements, and ERPs

Figure 1.
Examples of physically salient stimuli that are used as visual warning signals in day-to-day life. Researchers debate whether these signals actually have the power to attract attention automatically, independent of a person's knowledge and goals.

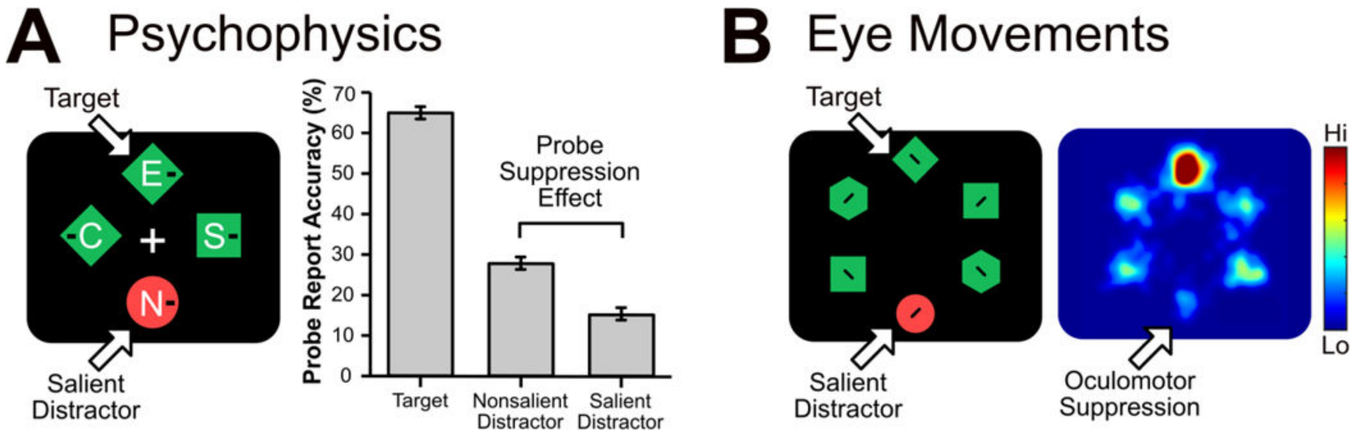

Figure 2.

Evidence of suppression of a salient distractor from psychophysics [8] and eye tracking [9]. (A) In the capture probe task, participants search for a target and make a speeded buttonpress to an oriented line inside the target (not shown here). One probe trials, letters appear briefly at each location and participants try to report as many letters as possible. he salient item is less likely to reported than baseline (the average of nonsalient distractors). (B) In eyetracking tasks, participants search for a target and attempt to ignore a salient distractor. As shown in the heat map, first eye movements are biased away from the singleton compared to nonsingleton distractors.

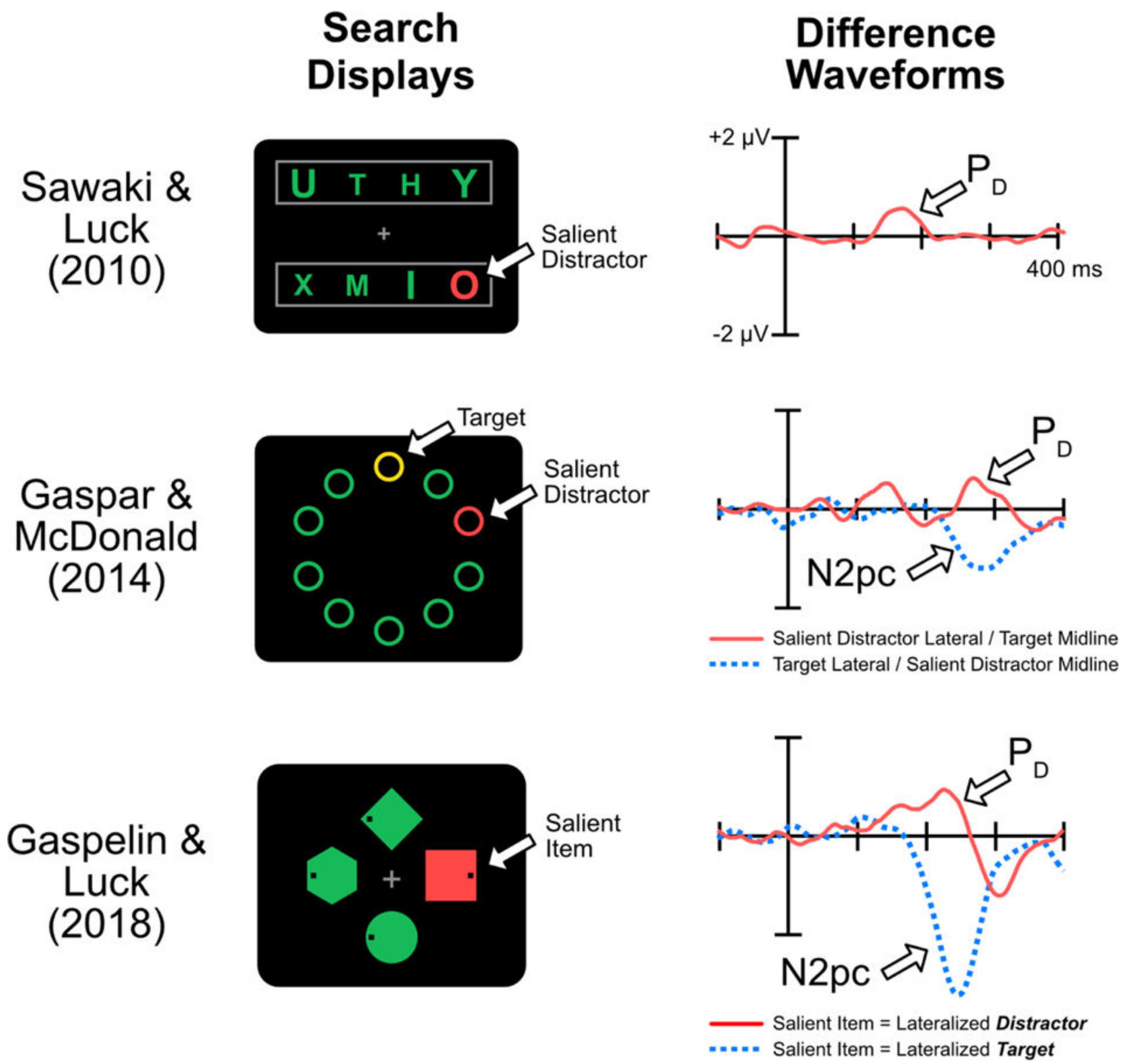

Figure 3.

Several studies have demonstrated that salient distractors elicit a suppression-related ERP component called the distractor positivity (P_D). The studies of Gaspar and McDonald (2014) and Gaspelin and Luck (2018) found that targets elicit an attention-related N2pc component, even if they are relatively salient.

Table 1

Common Theories of Attentional Capture: Summary, Predictions, and Recommended Readings

	Bottom-Up Models	Top-Down Models	Suppression Models
Summary	Certain types of salient stimulus features automatically capture visual attention	Attention is controlled by goals and experience — salience is irrelevant	Physically salient features attempt to drive visual attention, but can be suppressed to prevent attentional capture
Real-World Predictions	Rampant distraction by physically salient objects	Failure to notice seemingly salient warning signals (“tunnel vision”)	People can rapidly learn to ignore salient signals
Recommended Readings	[1,2]	[3–5]	[8,11,12,34]