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Attentional Mechanisms of Distractor Suppression

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Abstract

The ability to suppress distractors is critical for the successful completion of goal-oriented behaviors. This is particularly true for everyday behaviors that take time to accomplish and are frequently interrupted by unpredicted events (e.g., spotting a sale on a favorite drink while searching a grocery store for an apple). For one to continue with the intended goal, attention to the distractor must be reactively suppressed (i.e., terminated) so that the goal-oriented behavior may resume. Such reactive suppression can be contrasted with a proactive mechanism that anticipates the appearance of a distractor and suppresses related sensory processing in advance. In this review, I consider three aspects of distractor suppression: (a) the distinction between proactive and reactive mechanisms, (b) the conditions under which reactive distractor rejection can be rapid, and (c) the neural and cognitive processes necessary for controlling proactive and reactive distractor suppression.

Keywords

attention, suppression, distracter, rejection, inhibition

A hallmark characteristic of human cognition is the ability to flexibly adapt to changes in the current sensory environment. One way that flexible control manifests itself is through attentional mechanisms that suppress processing of information that has captured attention despite being irrelevant to current goals. The importance of reactive attentional control can be seen in the example of searching for an apple in the grocery store. The time in the store is mostly spent serially looking at and rejecting various objects as being task irrelevant (i.e., not the apple). The distractors we attend to may be perceptually salient (e.g., flashing advertisements) or have properties similar to apples (e.g., peaches), but if the distractors can be rapidly rejected, then it will take only a short time to find the apple. However, if a distractor holds our attention, then it may substantially delay our accomplishment of the final goal or even derail it entirely. Thus, the efficiency of completing goal-based behaviors depends on the speed with which distractor processing can be suppressed and attention can be disengaged and reoriented to a new object to resume search.

In this review, I will attempt to draw a distinction between the reactive suppression of distractors (i.e., disengaging from irrelevant stimuli) and proactive mechanisms (i.e., preventing attention to irrelevant objects in the first place), characterize influences on the speed of rejection, and discuss the known brain mechanisms underlying distractor suppression. Although I use the term "suppression" here to refer to the mechanisms that prevent or terminate attention to a distractor (either proactively or reactively), I note that analogous concepts have long been explored within literatures on inhibitory control in a variety of motor and cognitive domains (for a review, see Bari & Robbins, 2013).

What Advantages Are There for a Reactive Mechanism?

When proactive suppression is possible, behavior tends to be optimal. This is because sensory responses associated with distractors are suppressed before they appear and progress on the task at hand can proceed uninterrupted. Such proactive suppression can occur either as an automatic consequence of prioritizing target features

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or as a result of the active suppression of expected distractor features. To return to my opening example, the former may occur when prioritizing the color and shape of red apples automatically suppresses opponent features, such as those of green vegetables (Awh, Matsukura, & Serences, 2003; Dosher & Lu, 2000); the latter would occur when the presence of a specific distracting advertisement or pile of peaches is actively suppressed because it is expected based on prior experience in the same store (Arita, Carlisle, & Woodman, 2012; Treisman & Sato, 1990; Yantis & Egeth, 1999). However, some have argued that attention always precedes active distractor suppression (Lahav, Makovski, & Tsal, 2012; Moher & Egeth, 2012).

In daily life, attentional capture by irrelevant things is inevitable because we cannot always anticipate what distractors will look like, where they will be, or when they will appear. This is particularly true for perceptually salient objects that elicit a prepotent orienting response and for objects that match goal-relevant information held in memory. When unexpected distractors capture attention, they must be rejected reactively in order for one to return to the primary task at hand. Additionally, it has been argued that reactive mechanisms are more common than proactive ones because the continuous active maintenance of goal-related information necessary for proactive suppression is metabolically expensive and cognitively taxing (Aron, 2011; Braver, Gray, & Burgess, 2007). This has been most clearly articulated in work by Braver and colleagues with respect to working memory and cognitive control, in which they suggested that reliance on proactive versus reactive mechanisms may depend on individual and contextual factors, including age, strategic choices, impulsivity, and reward expectations.

Interestingly, it is yet to be discovered whether the relationship between proactive and reactive mechanisms is antagonistic or synergistic. For example, the ability to maintain attentional focus that underlies proactive suppression may work in opposition to mechanisms of attentional disengagement and shifting that underlie reactive rejection; alternatively, both types of suppression may tap into shared attentional-control abilities. Because attentional control is a core mechanism implicated in many clinical and developmental disorders, identifying the distinct and shared mechanisms of distractor suppression will be critical for understanding individual and population differences (Miyake & Friedman, 2012). Moreover, although the exact mechanisms of reactive distractor rejection are still to be discovered, it is clear that the speed of rejection is highly variable and inversely related to the behavioral cost of having been distracted. Thus, understanding the conditions that influence the speed and success of rejection is imperative to understanding how humans accomplish complex goals.

When Is Rejection Rapid?

The reactive suppression of distractors is most effective when it is fast, and there is evidence that both stimulus factors and individual differences may contribute to its speed. Typically, the impact of distractors is measured through visual search tasks, in which participants are asked to look for a target object that appears with a varying number of distractors (Fig. 1a). The increase in reaction times with the number of distractors (Fig. 1b) reflects the time it takes to process and reject each additional distractor. For example, it is estimated that it takes approximately 150 to 300 milliseconds to reject distractors that can be identified as task irrelevant only after being fixated; this amount of time is consistent with how long it takes to generate voluntary saccades, as well as estimates of attentional dwell time (Theeuwes, Godijn, & Pratt, 2004; Wolfe & Horowitz, 2004). Considerably shorter distractor-processing times have been reported, but it may be that the paradigms in which they were observed involved covert processing of multiple distractors at once or other strategic factors (Treisman & Gelade, 1980).

However, the speed of distractor rejection is variable and can be rapid even for salient distractors. For example, in studies by Theeuwes and colleagues using variations of the additional-singleton task, there are a number of static circles in which a target is expected to appear. On some trials, a distractor suddenly appears in an unexpected location. The abrupt onset produces a salient percept that frequently captures the first saccadic eye movement; for instance, in Godijn and Theeuwes's (2002) Experiment 1, this occurred on 28.5% of trials. However, these erroneous saccades had short amplitudes (e.g., an undershoot of 1.7° compared with 0.1°–0.5° for saccades to targets) and were followed by exceptionally short fixation durations (e.g., less than 100 milliseconds) that were immediately followed by a corrective saccade back to the target, or to another task-relevant object. Theeuwes and colleagues hypothesized that these saccade characteristics (Fig. 1c) reflected the rapid disengagement of attention from objects that were dissimilar to the target (Godijn & Theeuwes, 2002; Theeuwes, 2010).

In my lab, I and my colleagues have also found similar signatures of rapid rejection in a visual search task in which the probability of the distractor being perceptually salient was manipulated (Geng & DiQuattro, 2010). Salience in our case was defined by an object's being brighter and having higher contrast than other stimuli. The locations of the target and distractors were randomly assigned. When both stimuli had an equal probability of being salient (in Experiment 1), the salient distractor interfered with performance as expected. However, when only the distractor was salient (Experiment 2), trials with

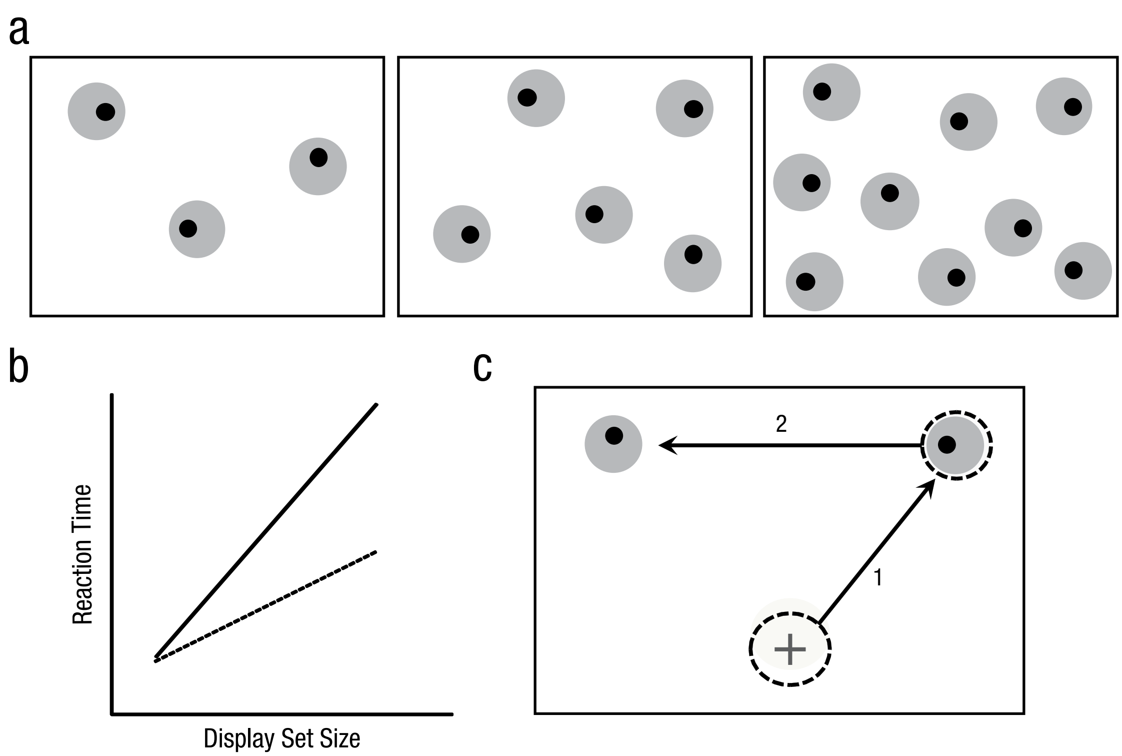

Fig. 1. Illustrations of behavioral measures of distractor processing. Panel (a) shows three example displays from a typical difficult visual search paradigm in which the number of distractors is varied on different trials (here, the target has donut hole on vertical midline, and distractors are 90° rotations). The graph in panel (b) shows the monotonic increase in reaction times with increasing numbers of distractors. Note that reaction times are approximately twice as long when the target is absent (solid line) compared with when it is present (dotted line) because, by chance, only a subset of distractors have to be rejected before a target is found. The exact slope of the search durations will vary depending on whether each distractor needs to be fixated serially or there can be some top-down guidance that helps proactively suppress distractor processing. The schematic in panel (c) illustrates typical eye parameters that reflect distractor processing and suppression: the saccade latency (i.e., how long it takes to initiate the first saccade; dotted circle around fixation), saccade amplitude (endpoint of arrow), fixation duration (dotted circle around the distractor), and destination of next saccade (e.g., to a target or another distractor).

salient distractors elicited shorter reaction times and higher accuracy (see also Vatterott & Vecera, 2012; Yantis & Egeth, 1999). This pattern was true even on trials in which the first saccade went to the salient distractor (57% of trials). Attentional capture by the salient distractor initiated a reactive response to rapidly reject the distractor and begin a corrective saccade, perhaps even while still executing the first saccade (Godijn & Theeuwes, 2002; McPeek, Skavenski, & Nakayama, 2000).

In addition to faster reactive rejection, there was a 19% decrease in the proportion of first saccades to the distractor when salience was anticorrelated with the target compared with when it was equally likely to be a property of the target or distractor (Experiment 1). This finding highlights the synergy between proactive and reactive mechanisms: Contextual knowledge about task-relevant features was used to facilitate performance reactively, with minimal costs to behavioral outcomes when proactive mechanisms failed to inhibit attentional capture (for any number of reasons, including mind wandering, fatigue, or stochastic neuronal noise). Interestingly, there were substantial individual differences in the ability to proactively suppress attention to the salient distractor (Mazaheri, DiQuattro, Bengson, & Geng, 2011), suggesting that individuals with better attentional control can avoid distraction more effectively in the first place.

The rapidly rejected distractors in these studies had three characteristics: (a) high salience (i.e., greater brightness, a sudden onset, or a pop-out color or shape), (b) a feature that mismatched known properties of the target (i.e., appearing in a task-irrelevant location or having a perceptual feature that was anticorrelated with the target), and (c) the presence of a potential target elsewhere that could trigger a competing saccade plan. It is not yet clear how each of these contribute to the likelihood of initial attentional capture or the components of rejection, such as attentional disengagement and reorienting. For example, although the previously reviewed studies used perceptually salient distractors that produced clear signatures of attentional capture, other data from my lab suggests that the speed of distractor rejection depends as much, or more, on the representational distance between the target and distractor than perceptual salience, per se. Distractors that were outside of the target category (in this case, color) had uniform rejection times, whereas those within the category boundary had rejection times that increased monotonically with physical similarity; moreover, this remained true when the category boundary shifted with learning (Geng & DiQuattro, 2014). Thus, when it comes to reactive distractor suppression, salience may just be an extreme version of dissimilarity (e.g., for a discussion on how to define similarity, see Dent, Allen, Braithwaite, & Humphreys, 2012).

There is a large body of research demonstrating the importance of category representations in perception and decision processes (Goldstone, Lippa, & Shiffrin, 2001). This work suggests that the mental template of the target is itself a type of category representation with flexible "tuning" that defines not only what features will be selected but also the speed with which distractors will be rejected (Duncan & Humphreys, 1989; Navalpakkam & Itti, 2007; Wolfe & Horowitz, 2004). Thus, although there is still much work to be done to fully understand how the mental representation of the goal state determines both proactive and reactive mechanisms of distractor suppression, it is clear that the ability to suppress distractors depends critically on expectations regarding the range of relevant and irrelevant stimuli that are likely to be encountered within the current environment.

What Are the Neural Mechanisms of Distractor Suppression?

There is a long history of research linking inhibitory control in different cognitive domains with prefrontal-lobe function (Bari & Robbins, 2013). Included is the idea that the prefrontal cortex is responsible for filtering task-irrelevant information and controlling distractor suppression (Kane & Engle, 2002; Shimamura, 2000). For example, there are now many studies that have found a relationship between activation in the prefrontal cortex and the proactive suppression of distractors on a trial-by-trial basis. In one study, for example, reaction times during a visual discrimination task were longer on trials with less prestimulus and stimulus-evoked activation in the inferior frontal gyrus and increased activation in the default-mode network (Weissman, Roberts, Visscher, & Woldorff, 2006). The researchers hypothesized that the reduction in frontal activation reflected greater mind wandering and, therefore, poorer task-related cognitive control. Similarly, we found that the presence of prestimulus frontal alpha predicted the first saccade would be captured by a salient distractor (Mazaheri et al., 2011). *Alpha* is a signature of cortical disengagement, which suggested that the disengagement of frontal regions from task-based goal maintenance resulted in a failure to suppress predictable attentional capture by a salient distractor.

It is clear, however, that the prefrontal cortex does not work in isolation (Fig. 2). For example, there is substantial evidence that prefrontal regions, particularly in the inferior and middle frontal gyri, interact with structures of the basal ganglia in situations of motor and cognitive inhibitory control (Aron, 2011; McNab & Klingberg, 2008). In my own work, I and a colleague found that the effective connectivity between the inferior frontal gyrus, the frontal eye fields, and the supramarginal gyrus (within in the temporoparietal junction) was configured to prioritize the suppression of salient distractors (DiQuattro & Geng, 2011). This suggested the interesting possibility that network coupling between prefrontal regions and task-specific regions (in our case, those involved in attentional control) is flexibly adjusted to optimize behavior in a specific context.

Evidence from electrophysiological recordings in monkeys has identified neurons in the dorsolateral prefrontal cortex (dlPFC) whose activity encodes where not to look, as well as those that encode where to look (Hasegawa, Peterson, & Goldberg, 2004). The increase in "don't-look" neuronal activity was specific to a distractor location and was greater on trials in which saccades to the distractor were successfully inhibited, which suggests that there is a signal for the active suppression of saccades to nontargets. More recently, activity in a more rostral portion of the dlPFC was found to reflect both proactive and reactive suppression (Suzuki & Gottlieb, 2012). In this study, correct behaviors were associated with less activity in the dlPFC in response to distractors, suggesting a suppressive mechanism within the dlPFC that inhibits erroneous actions. The authors suggested that the suppressive signal was related to linking sensory selection to behavioral outcomes. It is still somewhat unclear, however, how this signal in the dlPFC relates specifically to attentional control as opposed to associated eye movements or other motor actions.

Although decisional factors associated with distractor suppression appear to be controlled by the prefrontal cortex, there is evidence that suppression is implemented through modulations of sensory processing (Gazzaley et al., 2007; Ruff & Driver, 2006; Seidl, Peelen, & Kastner, 2012; Serences, Yantis, Culberson, & Awh, 2004), in a manner analogous to sensory enhancements of target features (Reynolds & Chelazzi, 2004). For example, measures of electrophysiological responses in humans using event-related potentials (ERPs) have identified the distractor-positivity (Pd) component, which occurs over occipital electrodes, as being linked to the suppression of

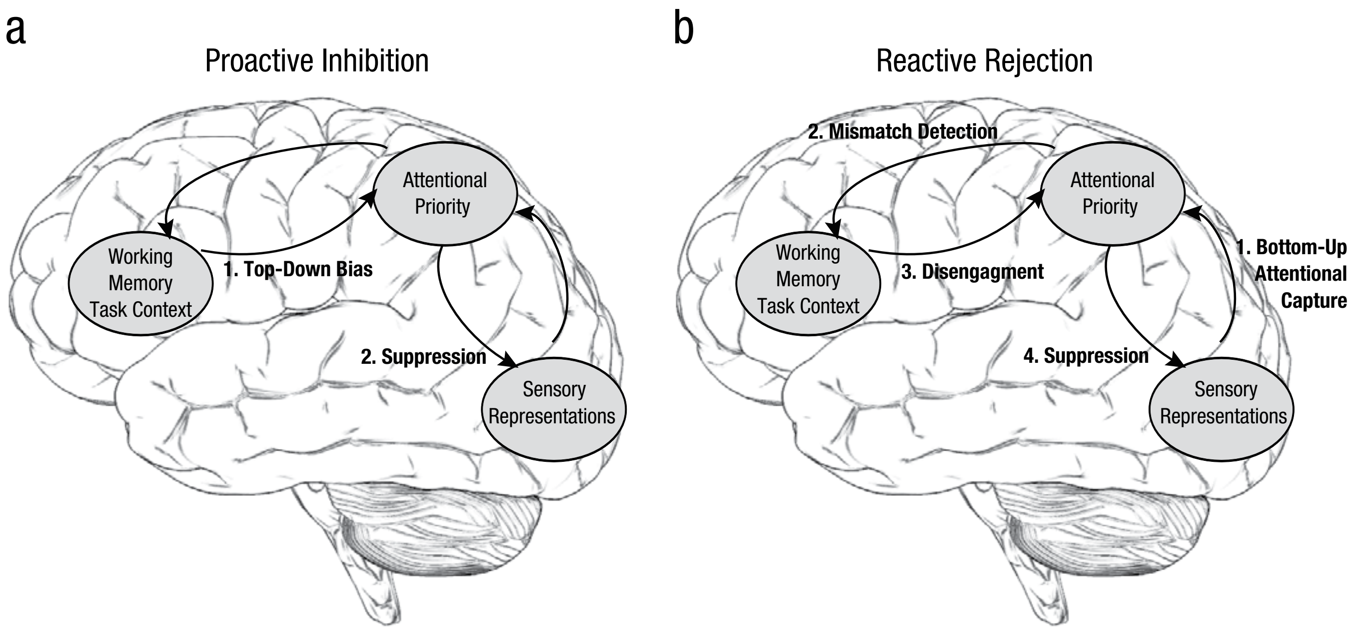

Fig. 2. Schematic illustration of the sequence of cognitive functions involved in (a) proactive suppression and (b) reactive distracter rejection overlaid on putative neural structures involved in maintaining each cognitive representation. Note that mechanisms of target selection are not illustrated, but would be expected to occur in parallel.

distractors (Hickey, Di Lollo, & McDonald, 2009). On trials in which the presence of Pd occurred without a preceding attentional shift, participants had faster response latencies (Jannati, Gaspar, & McDonald, 2013). The fact that this signature of stimulus suppression occurs both with and without a preceding shift of attention (Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2010) suggests that the sensory consequences of stimulus suppression are similar when it occurs proactively and reactively. Interestingly, other temporally earlier visual ERPs (e.g., early positive and negative peaks P1 and N1) were used to identify individual differences in the ability to reactively disengage from distractors that capture attention, which correlated with working memory capacity (Fukuda & Vogel, 2009, 2011). These results support the notion that reactive distractor suppression is under active control and that the speed of rejection may reflect domain-general cognitive abilities (Ikowska & Engle, 2010).

Conclusions

The ability to control attention is critical to everyday behaviors. In particular, the ability to control attention reactively, when distractors have captured our attention unwittingly, is a fundamental cognitive function that dictates the fluidity and efficiency of complex behaviors that take time to complete. Even though proactive suppression results in less distractor interference overall, there are many practical, cognitive, and metabolic limitations to its usefulness. Under these situations, a prompt reactive mechanism can make up for our previous failures and get behavior back on track without much delay. Although there is much we still do not understand about how attention to distractors is suppressed, the prefrontal cortex appears to be critical for integrating memory and decision processes necessary for setting attentional priority. There are open questions about many issues remaining, including identification of the cognitive and neural components of proactive and reactive distractor suppression, the reasons for moment-to-moment fluctuations in their use within an individual, and the sources of stable differences between individuals. Future research addressing these questions will elucidate how we are able to efficiently complete goal-oriented behaviors in daily life by flexibly relying on proactive and reactive mechanisms of distractor suppression.

Recommended Reading

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). (See References). A chapter that introduces the ideas of proactive and reactive control mechanisms.
Fukuda, K., & Vogel, E. K. (2011). (See References). A study that describes individual differences in the ability to suppress distractor information.
Geng, J. J., & DiQuattro, N. E. (2010). (See References). A study describing how reactive rejection can be rapid even after attention is captured by a salient stimulus.

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