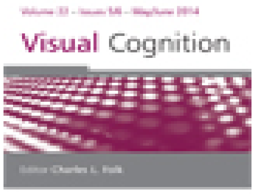


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# Unresolved issues in distractor suppression: Proactive and reactive mechanisms, implicit learning, and naturalistic distraction

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**ABSTRACT**
We acknowledge the empirical and theoretical advancements described within Luck et al. and commend the integration of viewpoints on the debate over attentional capture by salient distractors. Our commentary seeks to build on the conversation by drawing attention to open questions that remain about how proactive and reactive mechanisms might operate, the mechanisms of implicit learning, and how attentional capture might occur within the context of naturalistic behaviors.

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We commend the "rivalrous collaboration" by Luck, Gaspelin, Folk, and Theeuwes regarding a debate on attentional capture that has persisted over the last 25 years. In this commentary, we seek to continue the dialogue regarding unresolved issues in distractor suppression and focus on three points: The first discusses the idea of how proactive and reactive suppression might operate on priority maps, the second discusses mechanisms of implicit learning, and the last takes a step back to discuss the "big picture" question of what role attentional capture might play in naturalistic behaviors.

## Proactive and reactive suppression: Dichotomous or graded?

In the current perspective, all three theories appear to agree that reactive suppression operates by tamping down distractor salience at the level of the priority map after a distractor has captured attention, but proactive suppression bypasses the priority map and operates directly on gain control mechanisms in sensory maps. In this section, we visit the question of whether proactive and reactive mechanisms of distractor suppression are dichotomous states (Geng, 2014), or if they might be graded or probabilistic processes that act on priority maps at different "stages" of the visual and oculomotor systems (Sprague et al., 2018; Wolfe, 1994; Zelinsky & Bisley, 2015).

The criterion for successful proactive suppression is based on the absence (or below baseline levels) of attentional orienting or neurophysiological priority signals to a stimulus. However, several recent studies find evidence consistent with proactive suppression without the elimination or absence of stimulus-evoked responses. For example, studies show that reductions in behavioral interference by predictable singleton distractors are accompanied by reductions in stimulus-evoked responses or by changes in informational content within visual cortex (Adam & Serences, 2020; Noonan et al., 2016; van Moorselaar & Slagter, 2019, 2020; Won et al., 2020). The study by Won et al. (2020) also found that the changes in activation patterns within visual cortex are accompanied by the disappearance of distractor-evoked activations in parietal and frontal attentional control regions known to encode salient distractors (Bogler et al., 2011; Ipata et al., 2006). Changes in distractor encoding in visual cortex appeared sufficient to reduce the readout of saliency signals associated with a singleton distractor to parietal priority maps, but they did not necessarily result in the complete elimination of sensory and behavioral indicators of the salient distractor.

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Consistent with the notion that salient distractors that are well suppressed can nevertheless leave traces of processing, a recent study measured memory and awareness of a predictable color singleton during visual search using a "one-shot" memory probe (Won et al., 2021). Participants showed behavioral reductions in interference over repeated trials but still reported some residual memories and awareness of the distractor feature, albeit significantly degraded compared to distractors that were unexpected and captured attention (Won et al., 2021). It would be interesting to know if similar residual effects would be found for stimuli that are suppressed even before they are attended, as measured by the Pd ERP component, which is considered a signature of stimulus suppression (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018; Hickey et al., 2009; Sawaki & Luck, 2010).

Another reason why we may want to consider proactive and reactive suppression mechanisms as being graded is that while it is often assumed that only one form of suppression occurs within a single task design, there is evidence their use is more probabilistic. For example, although salient distractors (defined by luminance, contrast, color) are less likely to capture attention when they are predictably task-irrelevant, they still capture the first eye-movement on a subset of trials; however, the fixation duration on distractors is often extremely short (e.g., less than 100 ms) suggesting that a competing motor plan was initiated even as the erroneous first saccade was executed (Born et al., 2011; Geng & Diquattro, 2010; Godijn & Theeuwes, 2002; McPeek, 2006; Moher et al., 2011). In addition to trial-by-trial variability, the likelihood of task interference by a salient distractor correlates with a number of individual difference measurements, such as working memory, mind wandering and distractability, and video game expertise (Chisholm et al., 2010; Forster & Lavie, 2014; Fukuda & Vogel, 2011).

One curiosity in the distractor suppression literature, however, is that most demonstrations of proactive suppression do not appear to involve explicit sustained cognitive control mechanisms that rely on working memory. This contrasts with the original dual mechanisms of control model that defined proactive cognitive control by the need for sustained and anticipatory maintenance of information, which is cognitively demanding (Braver, 2012). Thus, we may need better models of proactive and reactive suppression if we are to fully understand how distractors are ignored.

## Implicit learning: Control state, sensory attenuation, or expectation suppression?

Luck et al., describe the control state as containing two classes of mechanisms: one based on explicit goals held in working memory and another based on implicit memory or selection history. The concept of a control state originates from models of target selection (Folk et al., 1992; Jonikaitis & Moore, 2019), and implies that both explicit and implicit mechanisms of distractor suppression are *of a kind* and function to actively control attention away from visual distractors. This is analogous to control mechanisms that drive attention towards targets, but mechanisms of distractor suppression may operate on principles that differ from target selection (Chang & Egeth, 2019; Lega et al., 2019; Noonan et al., 2016; van Moorselaar & Slagter, 2019).

One reason to wonder if effects of learned suppression attributed to implicit learning are truly a "control state" comes from a growing body of evidence that some effects of learned suppression do not depend on goal-driven attentional modulations, *per se*, but rather on sensory mechanisms such as repetition suppression (Fecteau & Munoz, 2003; Goschy et al., 2014; Hansmann-Roth et al., 2019; Kristjansson & Asgeirsson, 2018), habituation (Bonetti & Turatto, 2019; Turatto et al., 2018; Won & Geng, 2020), adaptation (Liu et al., 2014), or expectation suppression (Noonan et al., 2018; Richter et al., 2018). For example, recent studies have found that passive exposure to salient stimuli reduces interference when they later appear as "distractors" (Turatto et al., 2018). Such findings suggest that distractor suppression does not require active selection history: stimuli do not have to be tagged as distractors in order to be attenuated in sensory cortex. Intriguingly, passive mechanisms such as habituation have been hypothesized to be the default sensory response to stimulation, and that release from habituation only occurs when attention mechanisms enhance responsivity (Ramaswami, 2014; Rankin et al., 2009).

The idea that some effects attributed to distractor suppression may reflect automatic sensory attenuation is consistent with results described in the previous section showing that changes in visual processing are associated with reductions in distractor interference without “top-down” contributions from frontoparietal regions (Adam & Serences, 2020; De Weerd et al., 1999; Noonan et al., 2016; Won et al., 2020). Contributions from automatic processes specific to sensory attenuation may also explain why distractor suppression appears highly sensitive to implicit regularities, but not explicit goals; conversely target selection operates effectively through explicit goal states as well as implicit learning. Future work isolating task-unrelated mechanisms that contribute to distractor suppression will be important for understanding how task-irrelevant information is deprioritized, regardless of whether it is salient or not.

Another reason to consider the utility of lumping all task-related suppression under a single concept of a control state is that explicit and implicit mechanisms may have different neural and informational sources. When target information from implicit sources such as spatial probabilities have been pitted against explicit information about spatial cues, stimulus saliency, or reward associations, the implicit and explicit sources produce additive effects on behavior (Awh et al., 2005; Garner et al., 2021; Geng & Behrmann, 2005; Jiang, 2018; Kim & Anderson, 2019; Stankevich & Geng, 2014). Such results imply that the two types of target information have separable sources and predicts that changing the mechanisms of one might not affect the other. This appears to be the case: when endogenous goals to shift spatial attention are disrupted by brain damage, implicit learning of spatial probabilities is preserved (Geng & Behrmann, 2002; Goldfarb et al., 2016). Although more work is necessary to determine whether explicit and implicit information contributions to distractor suppression rely on separable mechanisms, using a common “control state” label may potentially obscure important differences.

## What is the point of it all: Information gathering and natural environments

The debate described by Luck et al. over the question of if and when attentional capture is obligatory has almost exclusively been tested within short experimental trials with sparse stimulus displays, limited trial histories, and physically salient (color singleton) distractors. Such paradigms are the mainstay of our field, but in our opinion, one reason different theories have reached an impasse might lie in how the question is asked. A hint of this comes from the discussion raised by Theeuwes and colleagues regarding the conditions that make a non-target unambiguously salient and whether proactive suppression can ever occur for those stimuli. One might ask what are the natural conditions under which a “distractor” is unambiguously salient.

The real-life scenarios that populate introductory paragraphs of manuscripts in our field are one place to begin inquiry: illustrations such as orienting towards flashing ambulance lights and sirens, brightly colored animals in neutral-colored backgrounds, or a cell phone ringing in a quiet study hall. All of these scenarios call upon our intuitions of physically salient events that we know capture attention and are nearly impossible to suppress even when the active control set does not include these stimuli. They capture attention because they are highly distinct from other objects in the environment and are also surprising and unexpected. These naturalistic scenarios also lay bare the importance of multisensory information. Unexpected auditory and audiovisual stimuli are particularly potent signals for capturing visual attention, potentially because they signal previously unseen stimuli that may warrant an action response or reinforce the saliency of an already visible object (Koelewijn et al., 2010).

Questions remain over the role that surprise from audition, vision, and other sensory systems play in the strength and automaticity of attentional capture. Recent literatures have begun to carefully consider surprising events in terms of their information value (Auksztulewicz et al., 2017; Gottlieb et al., 2014; Summerfield et al., 2008). A novel, surprising, stimulus is rarely a de facto “distractor” given its potential requirement for a response; perhaps many real-world stimuli capture attention despite the current control set in order to alert the organism to new information of potential relevance, even if it is not relevant to the current “task.” Thus, not all “nontargets” are “distractors” and further work is needed to better understand how apparently task-irrelevant information has utility for immediate or long-term behaviors in natural environments (Hickey et al., 2019). Achieving this goal will likely require the integration of approaches that are more naturalistic, using virtual environments and multisensory and dynamic stimuli (Bohil et al., 2011; Matusz et al., 2019).

## Conclusion

The perspective piece by Luck et al., provides an important summary of the history and current viewpoints on attentional capture by salient distractors. Our commentary seeks to continue to the conversation by underscoring open questions about what distraction is, how it is attenuated and suppressed, and what purpose it might serve in real-world behaviors.

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