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Progress and Remaining Issues: A Response to the Commentaries on Luck et al. (2021)

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Abstract

Luck et al. (2021) reviewed evidence that observers can learn to suppress attentional capture by salient distractors. Several commentaries were written in response to this review paper, many of which raised important and interesting issues. Here, we respond to these commentaries. Although there has been substantial progress in the attentional capture debate, there are still remaining issues that need to be addressed before the debate is completely resolved. Specifically, we summarize the need for an independent measure of bottom-up salience and better metrics of how attentional control unfolds over time. Ultimately, the field may need a more refined theoretical model of visual attention that distinguishes between attentional priority, attentional orienting, and attentional engagement.

Keywords

attentional capture; visual attention; suppression; salience

We would like to thank all of the individuals who took the time to provide commentaries on our review paper. The commentaries raised many interesting ideas and important issues. Here, we focus on some of the recurring themes that we think are particularly valuable for continuing to move the field forward. Our response will focus on four key issues that were raised in multiple commentaries: set sizes and bottom-up salience, reactive versus proactive inhibition, attentional priority versus attentional capture, and stages of attentional capture.

Set Size and Bottom-Up Salience

An issue that often lies in the background of research on attentional capture is that most studies lack a formal definition of salience or an independent measure of the salience of the stimuli. This issue was brought to the foreground in several of the commentaries. For example, Chang et al. (2021) provided an in-depth discussion of what exactly bottom-up salience is and proposed a potential method for verifying bottom-up salience via

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computational models of salience. Additionally, Ruthruff et al. (2021) questioned whether the bottom-up salience signal of color singletons ever have the power to attract attention. Finally, some of the commentaries critiqued some of our prior empirical work on capture for using low set sizes (Kerzel et al., 2021; Liesefeld et al., 2021), which can reduce salience as well as producing atypical search strategies.

The issue of salience and set size has arisen previously in the capture literature (Theeuwes, 2004), but it has recently come to prominence as a potential alternative explanation for studies in which irrelevant color singletons appear to be suppressed rather than capturing attention (reviewed in our section of Luck et al., 2021). This evidence of suppression has recently been challenged by Wang and Theeuwes (2020), who have suggested that the color singletons in these studies were not sufficiently salient to capture attention and thus were easily suppressed (see also Theeuwes' section in Luck et al., 2021). For example, Gaspelin et al. (2015) used a probe technique to demonstrate that processing at the location of an irrelevant color singleton was suppressed below baseline, but some of the experiments in that study used a set size of 4 items. Wang and Theeuwes (2020) replicated this paradigm but increased the set size to 10 items with the goal of increasing the bottom-up salience of the color singleton. They replicated the finding of probe suppression at the singleton location with a set size of 4 items. At a set size of 10, however, probe processing was increased above baseline at the singleton location. This was taken as evidence that salient items automatically capture attention, but only when they are made sufficiently salient to overpower attentional suppression.

The commentary by Chang et al. (2021) noted that saliency is not a well-defined term, and they reviewed several pieces of prior evidence that a color singleton is actually quite salient at set size 4. They also introduced one new piece of evidence: When salience models that are particularly effective for artificial displays (Kotseruba et al., 2020) were applied to the kinds of stimuli used in previous experiments (e.g., Gaspelin et al., 2015), a singleton at set size 4 was quite salient. They also noted that a recent paper by Stilwell and Gaspelin (in press) had identified a flaw with the Wang and Theeuwes (2020) study: At set size 10, there is a clear floor effect that makes it nearly impossible to detect suppression effects. When this flaw was corrected, Stilwell and Gaspelin found that color singletons were suppressed even at large set sizes of 10 or 30 items. This pattern of results occurred even when the exact stimuli of Wang and Theeuwes (2020) were used. Thus, there is strong evidence against the claim that singleton suppression can only occur at low set sizes or when the singleton is weakly salient.

In addition to the issues raised by Chang et al. (2021), there are other reasons to doubt that color singletons can be suppressed only when they are weakly salient. For example, many previous ERP studies have shown suppression effects (a P_D component) at relatively high set sizes in which the singleton should have been highly salient (e.g., a set size of 10 in Gaspar & McDonald, 2014 or a set size of 8 in Sawaki & Luck, 2010). Additionally, many previous studies of eye movements initially found suppression effects at set sizes of 6 (Gaspelin et al., 2017). Later studies demonstrated that color singletons were sufficiently salient to capture attention when their color was unpredictable (Gaspelin et al., 2019; Gaspelin & Luck, 2018a). If the color singletons lacked sufficient salience, they should have not captured attention under these conditions.

The central problem highlighted by many of the commentaries is that salience is not well defined, and the field lacks well-established methods for assessing bottom-up salience. Most previous studies have designed salient stimuli based upon intuition about what “pops out” in a search display. This makes it challenging to refute claims that the suppressed stimuli actually had low bottom-up salience. Whenever a salient item fails to capture attention, a salience-based account could simply argue that the item was not actually salient enough. Without some independent measure of bottom-up salience, this low-salience claim becomes practically unfalsifiable. To move forward, therefore, the field needs approaches for independently verifying the salience of color singletons.

Chang et al. (2021) introduced the possibility of using computational models to independently verify the salience. Although this approach can be valuable, these models are based on theories of salience and may not directly correspond to the actual perception of bottom-up salience in human observers (Kotseruba et al., 2020). Therefore, other psychophysical approaches need to be developed to verify the salience of suppressed items.

In summary, there is reason to doubt the claim that highly salient items cannot be suppressed. But until direct measures of bottom-up salience are developed, it will be difficult, if not impossible, to falsify the claim that suppressed items were not sufficiently salient.

Reactive Suppression vs. Proactive Suppression

Another issue mentioned by several of the commentaries relates to the timecourse of suppression and whether suppression occurs before the first shift of covert attention (Al-Aidroos, 2021; Donk, 2021; Feldmann-Wüstefeld, 2021; Geng & Duarte, 2021; Won, 2021; Zivony, 2021). When studying attentional suppression, it is important to distinguish between proactive suppression and reactive suppression (Geng, 2014). *Proactive suppression* is suppression that occurs before the first attentional shift, thereby preventing attentional capture. For example, suppression may occur before the search array appears to anticipatorily suppress a known-to-be-irrelevant location. Likewise, suppression may occur rapidly after the onset of the search display to inhibit items with task-irrelevant features before the first shift of covert attention occurs. *Reactive suppression*, on the other hand, is suppression that occurs after initial attentional allocation to an item (Moher & Egeth, 2012; Sawaki et al., 2012). Thus, reactive suppression does not prevent attentional capture but would aid in recovery from attentional capture.

One of the key outstanding questions in research on attention capture raised by Luck et al. (2021) is whether salient items can be proactively suppressed. The contingent capture and signal suppression accounts propose that search items can be proactively suppressed when they appear in a task-irrelevant location or when they possess a task-irrelevant feature (Gaspelin & Luck, 2018c). Salience-based accounts, however, commonly suggest that proactive suppression of salient items is only possible when the location of the salient item is known in advance. When the location of the salient item is unknown, salient items can only be reactively suppressed after initial capture. There are a few accounts of how a reactive suppression process might explain the absence of attentional capture effects in the studies that appear to show that salient stimuli can be ignored. One common variant is the *rapid disengagement account*, which proposes that salient items always initially capture attention, but are rapidly suppressed after capture (Theeuwes et al., 2000). This makes RT-based capture effects difficult to observe, especially in paradigms where salient items appear before the search array (Folk et al., 1992). As noted in the commentary by Eimer (2021), there is a lack of evidence that singletons can be suppressed in such paradigms.

Although there is evidence that rapid disengagement may happen in some situations (Geng & Diquattro, 2010), there is some strong evidence against the idea that rapid disengagement can explain all cases of lack of capture. For example, in the spatial cuing paradigm, salient cues fail to produce cue validity effects even when the cue and search items are presented simultaneously (Chen & Mordkoff, 2007). This 0-ms SOA should leave no time for rapid disengagement from the cued item. Similarly, many studies using the capture-probe paradigm have observed probe suppression effects even with extremely brief probe durations (100 ms) that would leave insufficient time for multiple attentional shifts (Gaspelin et al., 2015; Stilwell & Gaspelin, in press). Furthermore, many ERP studies indicate that salient objects can be ignored without any evidence that they are initially attended (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018b; Lien et al., 2008; Sawaki & Luck, 2010). In short, there is already fairly compelling evidence that salient items can be proactively suppressed to prevent capture, which seems to refute rapid disengagement accounts of attentional capture.

One interesting possibility mentioned by Geng and Duarte (2021) is that proactive and reactive suppression may not be mutually exclusive cognitive mechanisms. There are multiple parallel pathways in the brain, and perhaps some could be suppressed while other show capture. This would effectively allow both reactive and proactive mechanisms to operate in parallel. A related idea, discussed by Al-Aidroos (2021), is that there may be multiple levels of attentional selection during visual perception. Similarly, Won (2021) discussed recent research indicating that participants can learn to passively suppress distractors via habituation. It therefore seems possible that inhibition may not reflect a uniform cognitive process and may occur at various stages during visual cognition (see also Zivony, 2021).

One account that blends aspects of reactive and proactive suppression was suggested by Donk (2021). According to this account, shifts of covert attention are initially biased by the bottom-up salience and top-down control is delayed. This is because the bottom-up salience signal fades over time and gradually becomes weaker than top-down signals elicited by task-relevant stimuli. Thus, the only way to ignore salient objects is to slow overt eye movements or covert attentional allocation until the priority weight of the salient item has sufficiently decayed below the level of task-relevant items. Although this account might seem plausible, it does not fit the previous eye movement results. For example, Gaspelin et al. (2017) found that saccadic eye movements to salient distractors were suppressed, even in the fastest quartile of eye movements (ca. 175 ms). Also, as mentioned previously, attentional suppression can occur in capture-probe paradigms with very brief durations of 100 ms (Gaspelin et al., 2015; Stilwell & Gaspelin, in press). These results indicate that proactive attentional suppression can occur so rapidly that there is no need to postulate an initial attentional bias toward the salient object.

Ultimately, in order to understand the timecourse of attentional control, we may need better measures of how attentional selection unfolds across time. One possibility outlined by Feldmann-Wüstefeld (2021) is that the timecourse and relationship of the P_D/N2pc components may provide helpful hints for how attentional control is implemented and this may ultimately result in a theoretical framework for suppression that is more complicated than that proposed by Luck et al. (2021). One interesting idea proposed by Grubert and Eimer (2018) is that attentional control settings may “ramp up” in anticipation of the search display (see also Olmos-Solis et al., 2017). Their ERP approach may be useful for future studies of how attentional suppression is used to avoid color singletons and other salient distractors. It is also possible that other approaches such as EEG decoding could provide useful insights into how attentional suppression is implemented over time (Bae & Luck, 2018; Fahrenfort et al., 2017; Foster et al., 2020).

Attentional Priority vs. Attentional Capture

Several of the commentaries suggested that it may be useful to think of attentional capture in terms of a continuously variable “attentional priority” signal rather than a winner-take-all process (Anderson, 2021; Lamy, 2021; Leonard, 2021; Slagter & van Moorselaar, 2021). The basic idea is that there is an attentional priority map in which each object in the visual field is assigned a priority weight that represents the relative likelihood that an item will be attended (e.g., see Fig. 2 in Luck et al., 2021). The priority weight for a given item may be based upon some combination of task relevance, bottom-up salience, match with recent experience, and factors related to reward history and emotional valence. As eloquently reviewed by Leonard (2021), this general framework strongly resembles the *biased competition model* (Desimone & Duncan, 1995) in that the item with the highest priority weight will ultimately “win” the competition amongst items and actually attract visual attention. It also resembles a Guided Search models, which have long included an attentional priority map (Wolfe, 2021). It is also entirely consistent with the signal suppression hypothesis as outlined in Luck et al., (2021).

In an excellent commentary, Lamy (2021) suggests that a potential resolution to the attentional capture debate is that priority weights may be determined by both bottom-up and top-down factors. Similarly, Slagter and van Moorselaar (2021) suggest that attentional priority may be determined by a combination of bottom-up salience, top-down relevance, and implicit learning in a predictive coding model. We generally agree with both commentaries that this seems like a potentially promising resolution. One issue worth highlighting is that the major contribution of the signal suppression hypothesis is that salient items can sometimes be suppressed below baseline levels. Original formulations of the signal suppression hypothesis proposed that a suppressive process directly decreased the priority weight of the salient item at the stage of the priority map (i.e., by decreasing the *attend-to-me* signal; Sawaki & Luck, 2010). However, the current version of signal suppression hypothesis (see Figure 2 in Luck et al., 2021) proposes that a suppressive process decreases the feature gain of the salient item *before* the priority computation, so that the salient item never produces a strong priority value (Gaspelin & Luck, 2018c). This is because several studies seem to indicate that participants learn to suppress singletons based upon specific feature values, such as the color orange (Gaspelin & Luck, 2018a; Stilwell & Vecera, 2020). If participants could suppress items based upon their priority weight, as originally proposed by the signal suppression hypothesis, the specific features of the to-be-ignored items should not matter.

One inherent benefit of thinking in terms of attentional priority is that priority may accumulate over an extended period of time and this accumulation process may be useful for explaining several phenomena related to visual search. For example, Lamy and colleagues have recently proposed that, in the spatial cuing paradigm, attentional priority may accumulate at the cued location without actually attracting attention to the cue itself *(the priority accumulation framework*; Lamy et al., 2018). This type of accumulation could potentially explain several apparent discrepancies related to modulations of search difficulty and compatibility effects from cued items in the spatial cuing paradigm. Additionally, accumulation of attentional priority could potentially explain intertrial priming effects. For example, we have shown that attention seems to be strongly attracted to the previous-trial target location (Talcott & Gaspelin, 2020; see also Maljkovic & Nakayama, 1996). It is possible that once a target is located on a given trial, the attentional priority of that location is automatically boosted on the next trial.

In summary, thinking about attentional capture in terms of attentional priority could offer a compelling explanation of many attentional phenomena. However, it is currently challenging to understand attentional priority and how it accumulates because there are not well-established methods to directly measure priority independently of its effects on attentional orienting.

Breaking Down Attentional Capture into Distinct Stages

Some of the commentaries suggested that attentional capture involves several distinct cognitive stages. Most notably, Anderson (2021) discussed some of the potential pitfalls in defining “attentional capture” as a unitary cognitive event. The basic idea is that attentional capture may consists of several distinct cognitive events and ignoring this possibility will lead to inherent confusion in the attentional capture debate.

A specific version of this general idea was suggested by Zivony (2021), who argues that attentional capture consists of an *orienting* stage that may or may not be followed by an *engagement* stage. In other words, covert attention may shift to a specific location, but it may or may not engage upon that location to deeply process the object at the location. Orienting to a salient distractor may prevent attention from being oriented toward the target, leading to impaired target processing when a salient distractor is present compared to when no salient distractor is present. However, this may occur even if attention is not *engaged* on the salient distractor. This explains why abrupt onsets can cause large spatial cuing effects without corresponding response compatibility effects (Gaspelin et al., 2016; Maxwell et al., 2020; Zivony & Lamy, 2018). We would like to add a related possibility, namely that the high priority signal generated by a salient distractor may prevent attention from being oriented toward the target even if attention is not actually oriented to the distractor (similar to a *filtering cost*; Becker, 2007).

The idea that attention involves several distinct mechanisms was previously highlighted by Prinzmetal et al. (2005), who proposed that attentional allocation may involve both *channel selection* and *channel enhancement*. Channel enhancement improves the perceptual representation to result in a clearer representation of the attended item. Channel selection, on the other hand, affects a decision process about whether the attended location is truly the target location. A similar distinction between the *control of attention* and the *implementation of selection* was made by Luck and Gold (2008) to explain patterns of attentional dysfunction in neurological and psychiatric disorders. Interestingly, Prinzmetal et al. suggested that different kinds of tasks may encourage channel selection versus channel enhancement. For example, voluntary attentional shifts elicited by predictive cues seem to result in channel enhancement, whereas involuntary shifts of attention elicited by nonpredictive cues seem to result in channel selection. The notion of channel enhancement is conceptually similar to the concept of attentional engagement raised by Zivony (2021), and some additional insights might be gained by revisiting Prinzmetal's work in this area.

A potential shortcoming of the attentional engagement account is that, like the rapid disengagement account, it could be difficult to falsify. For example, if a salient item fails to elicit a compatibility effect or some other identity intrusion effect, a salience-based account could suggest that the salient item did capture attention but that was not engaged upon. This would be potentially dangerous because it would allow salience-based accounts to ignore any disconfirmatory evidence that suggests that salient items can be suppressed. Therefore, it seems necessary to establish clear metrics of both attentional orienting and attentional engagement.

Conclusions

In summary, we are extremely grateful for all of the commentaries. Although there were some criticisms of our proposed framework, we found all of the discussions to be very constructive and helpful. We hope that the current theoretical framework can serve as a springboard for future investigations of attentional capture. The commentaries (and the initial review) have identified some remaining issues that need resolution in the attentional capture debate. We look forward to watching the field grow and move past the theoretical stalemate that has pervaded the attentional capture literature for the past several decades.

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