Learned spatial suppression is not always proactive

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Abstract

Learning to ignore distractors is critical for navigating the visual world. Research has suggested that a location frequently containing a salient distractor can be suppressed. How does such suppression work? Previous studies provided evidence for proactive suppression, but methodological limitations preclude firm conclusions. We sought to overcome these limitations with a new search-probe paradigm. On search trials, participants searched for a shape oddball target, while a salient color singleton distractor frequently appeared in a high-probability location. On randomly interleaved probe trials, participants discriminated the orientation of a tilted bar presented briefly at one of the search locations, allowing us to index the spatial distribution of attention at the moment the search would have begun. Results on search trials replicated previous findings: reduced attentional capture when a salient distractor appeared in the high-probability location. However, critically, probe discrimination was no different at the high-probability and low-probability locations. We increased the incentive to ignore the high-probability location in Experiment 2 and found, strikingly, that probe discrimination accuracy was greater at the high-probability location. These results suggest that the high-probability location was initially selected before being suppressed, consistent with a reactive mechanism. Overall, the accuracy probe procedure demonstrates that learned suppression is not always proactive, even when response time metrics seem consistent with such an inference.

Keywords: Attention, Attentional Capture, Distractor Suppression, Implicit Learning

Public Significance Statement

We live in a visual world filled with enormous distractions, and the visual system copes with them by suppressing irrelevant information. For example, people may learn to ignore a flashing billboard they drive past everyday. The current study examined the underlying mechanism of spatial suppression and showed that participants selected a to-be-ignored location prior to suppressing it, indicating a reactive suppression strategy. These results invite a reinterpretation of how learned spatial suppression takes place and suggest that people may not completely avoid attending to distracting information; instead, they may anticipate where a distractor will appear so that they can rapidly handle it.

Introduction

Our visual environments are complex and, at any given time, various aspects of these environments compete for our attention. As such, learning to ignore distracting information is critical in order to selectively process relevant information and effectively navigate the visual world. Although it is often assumed that a physically salient item -- i.e., one that differs from other objects in terms of a basic feature such as color -- automatically attracts our attention and produces a detrimental effect on target search (known as attentional capture; e.g., Theeuwes, 1992), we can still ignore distracting items based on explicit or implicit information about their features (Chang & Egeth, 2019, 2021; Cunningham & Egeth, 2016; Feldmann-Wüstefeld et al., 2019; Gaspelin et al., 2015; Gaspelin & Luck, 2018a; Sawaki & Luck, 2010; Vatterott & Vecera, 2012), as well as locations (Chang et al., 2019; Goschy et al., 2014; Leber et al., 2016; Wang & Theeuwes, 2018a, 2018b).

It has been proposed that observers can suppress a location that consistently and frequently contains a distractor (Goschy et al., 2014; Wang & Theeuwes, 2018b). That is, when a salient distractor is presented in one location more often than in others, observers can learn this statistical regularity and suppress the high-probability distractor location (Wang & Theeuwes, 2018a, 2018b). Such suppression manifests as attenuated attentional capture when a salient distractor appears in the high-probability location relative to a low-probability location, and slower target detection when a target is presented in the high-probability location.

How does such suppression work? Previous studies have largely focused on two possible mechanisms: proactive and reactive. Proactive suppression occurs when a critical spatial location is suppressed before the physical stimuli appear, while reactive suppression occurs when attention first engages with the stimulus (i.e., initial selection) in the to-be-suppressed location before disengaging from and actively suppressing it (for reviews; Geng, 2014; Theeuwes et al., 2022). In a typical paradigm used to evaluate the mechanism that supports suppression, participants perform a task that includes a combination of search trials and probe trials. On search trials, participants search for a target presented among nontargets (e.g., a circle among diamonds). On some of these trials, a salient distractor (e.g., a red item among green items) also appears in the display, capturing attention and slowing reaction times to the target. The salient distractor appears more frequently in one location than in others, and reaction times are less impaired when the distractor is in this high-probability location (i.e., suppressed) compared to the low-probability locations. On interleaved probe trials, a probe task is used to examine the allocation of attention at the time the search display would have onset. Probe tasks typically consist of the detection of an onset or offset of a stimulus to assess the distribution of spatial attention at the moment the probe is presented (Kim & Cave, 1995). According to the proactive account, if a location is suppressed prior to the onset of a display, detection and processing of a probe item presented in the suppressed location would be impaired compared to neutral locations. In contrast, the reactive account claims that suppression occurs only after a location is first attended (Geng, 2014). When suppression is reactive, the detection and processing of a probe item in the suppressed location would be initially enhanced compared to neutral items.

Most studies using search and probe trials have supported a proactive mechanism of learned spatial suppression (Huang et al., 2021, 2022; Kong et al., 2020). However, there are important caveats in the methodologies and interpretations of each of those studies. Principal among these is how and when the probes were presented. In the previous work, the probes were only presented after search or placeholder displays. In these cases, it would be possible to shift attention first to the high-probability location and then disengage, such that any facilitation of processing at that location would not be detectable by the time the probe appeared.

For instance, in Kong et al. (2020), probe trials always followed an initially presented search display. On probe trials, participants were asked to recall the orientation of a probe bar presented briefly among an array of six bars. The results showed more response errors and more frequent guessing for a probe bar presented in the location that most frequently contained a salient distractor on search trials. The authors interpreted these results as evidence for proactive suppression. However, as mentioned above, having a search display consistently and immeidately precede a probe display may have allowed participants to select and then suppress the distractor location while a search display was present (prior to the appearance of a probe display), which may have resulted in a proactive-like pattern of data. In the study by Huang et al., (2021), a premask display containing dots within two superimposed shapes at each location preceded both search and probe trials. On probe trials, following the premask display, one of the dots either remained on screen or disappeared, and participants were asked to respond if one of the dots disappeared and withhold a response if it did not (see also Huang et al., 2022). Responses to a probe were slower when it was presented at the high-probability location (i.e., one that frequently contained a salient distractor on search trials) relative to low-probability locations, and the authors interpreted this finding as evidence for proactive suppression. However, since there was a contingency between premask and probe displays, it is possible that the suppression process started before the onset of probe displays. An 800-ms premask display provides quite enough time to select and then suppress the frequent location while a premask display is presented, which may have resulted in a proactive-like pattern of data.

Although previous studies on learned spatial suppression have argued for proactive suppression, it has been observed that reactive mechanisms play critical roles in suppression of distracting items in other circumstances. For example, when participants have foreknowledge about the feature or location of an upcoming distractor via trial-by-trial cues, they select the distractor feature or location prior to suppression, adopting a reactive strategy (Addleman & Störmer, 2022; Chang et al., 2019; Moher & Egeth, 2012). In the study by Moher and Egeth (2012), search performance was slower and less accurate following ignore cues (i.e., cuing the feature of an upcoming distractor), and when a probe dot briefly followed a search display and was presented at one of the search locations, probe-dot responses were faster at the cued distractor location than at nondistractor locations at the early SOA, showing that participants were selecting a nontarget item appearing in the to-be-ignored color early in their search process (see also Addleman & Störmer, 2022). In the study by Chang et al. (2019), a salient distractor was suppressed (i.e., attentional capture was absent) following ignore cues (i.e., cuing the location of an upcoming salient distractor), but responses were faster when the identity of a cued distractor ('b' or 'f') was compatible with the target identity ('B' or 'F'). The compatibility effect was observed regardless of cue type, demonstrating the cued distractor location was selected to the extent that its identity was processed.

While our discussion has focused on two mechanisms of suppression, additional factors may produce suppression-like effects, even in cases where suppression is not present at all. One such factor is *decision-related slowing* (Carmel & Lamy, 2014; Darnell & Lamy, 2021). If the observer associates a spatial location with distracting information, they may become slower to decide that task-relevant information is present there – even if spatial attention is distributed evenly across the display. This scenario predicts that, during search, objects in the high-probability location gain selection equally as quickly as those in low-probability locations, but if a target happens to appear in the high-probability location, participants will be slower to respond to it. Note that this factor alone cannot explain the previously described patterns of search performance (e.g. Wang & Theeuwes, 2018a, 2018b). Another related factor that can impact distractor processing is a process we can refer to as *differential disengagement*. That is, during search, participants may experience equal attentional capture by distractors at the high- and low-probability locations, but they are faster to disengage from distractors when they appear at the expected high-probability location.[1] Taken together, it is possible that decision-related slowing and differential disengagement could explain the search data without either proactive or reactive mechanisms. Furthermore, on probe trials, if reaction time measures are used, a pattern of data resembling proactive suppression may be observed, due to decision-related slowing in the high-probability location when attention is actually equally distributed. Therefore, it is important to try to tease apart these different factors when assessing whether proactive suppression can explain the results.

In the current study, we devised a new search-probe paradigm that overcomes the limitations of the prior studies and evaluates the various possible explanations underlying the previously-observed results. We specifically seek to examine whether the effects previously described as "learned spatial suppression" are driven by a proactive mechanism or not. This

[1] Note that disengagement – especially rapid disengagement – can be closely related to reactive suppression. Both have been described as ways to handle a distractor after first attending to it. However, we define rapid disengagement as quickly disengaging from a distractor location without necessarily suppressing that location. In the case of reactive suppression, it does necessarily involve disengagement from a distractor location, although the focus is not on the speed of the disengagement but rather the suppression that remains. In practice, both rapid disengagement and reactive suppression my co-occur frequently, although we do not test this relationship in the present study.

paradigm is designed to more accurately probe the spatial distribution of attention at the moment the search would have begun. Like in previous studies, on search trials participants implicitly learned statistical regularities of distractor locations. On probe trials participants responded to the orientation of a probe bar appearing at one location, and this probe task was specifically designed to be sensitive to assessing the mechanism of spatial suppression in three ways. First, we used a single-item display in which a probe bar was presented at each location equally often. This allowed for a direct measure of spatial attention because in a multi-item search display both feature-based and space-based attention contribute to selection (Addleman & Störmer, 2022). Second, probe trials appeared infrequently, and participants had no foreknowledge about when these probes would appear, so we can assume the participants encountered probe trials while they were preparing to search. Finally, and critically, we measured accuracy when a probe display was presented under a data-limited condition: we manipulated exposure duration of the probe bar and masked the probe display, limiting the duration of access to the stimulus input. This approach removes the possible effects of decision-related slowing that could arise when the probe bar is presented in a distractor-probable location, and it is more sensitive to early perceptual processing based on the distribution of attention (Norman & Bobrow, 1975; Santee & Egeth, 1982).

If a proactive suppression mechanism underlies the so-called "learned spatial suppression" phenomenon (the high-probability location is suppressed prior to the onset of the trial), our data-limited probe procedure should be sensitive to this suppression; specifically, probe discrimination should be poorer (i.e., lower accuracy) at the high-probability location than low-probability locations. If a reactive suppression mechanism underlies the phenomenon (suppression of the high-probability location follows rapid initial selection of that location), our probe procedure will reveal increased accuracy at the high-probability location relative to low-probability locations. It should be noted that our design does not provide predictions about what happens after the mask, and we focus on what the predictions are at the moment of the probe. Finally, if the phenomenon is produced by neither proactive nor reactive suppression, we will see no differences in probe accuracy between the high-probability and low-probability locations. As described above, this latter scenario could occur if the signature of suppression on search trials is due to decision/response factors (decision-related slowing and/or differential disengagement). As a secondary analysis, we will also evaluate the spatial distribution of the effect on search trials, following Wang & Theeuwes (2018a, 2018b)'s report of a spatial gradient of suppression. If such a spatial gradient of suppression is in place proactively at the moment that the search is expected to begin, then we should observe a similar spatial gradient in accuracy on the probe trials.

Experiment 1

On search trials of Experiment 1, a salient distractor was presented more frequently in the high-probability location, while a target was presented equally often at each location. Following Wang & Theeuwes's (2018b) initial finding, Failing et al. (2019) used this probability manipulation to disentangle the effects of a distractor probability manipulation from a target probability manipulation (i.e., to test suppression without biasing the spatial location of a target), allowing them to conclude that the observed suppression effect was due specifically to distractor probability, not target probability. On probe trials, a single probe bar was briefly presented and then masked, with equal probabilities across all stimulus locations.

Method

Transparency and Openness.

Below we describe the standard levels met by all the experiments in the present study with respect to the Center for Open Science's Transparency and Openness Promotion Guidelines (Nosek et al. 2015):

Citation: Although we did not use previously collected data by others, all code (e.g., toolbox) and methods developed by others are cited in this article.

Data and Research Population: The data were collected in 2022. All data have been made publicly available at the Open Science Framework and can be accessed at https://osf.io/4wjm5/. As the sample was comprised of primarily young adults enrolled in a college course, the generality of these results may be limited beyond this particular population.

Design and Analysis (Reporting Standards): The current study complies, to the best of our efforts, with the American Psychological Association's (APA) Journal Article Reporting Standards for Quantitative Research in Psychology (JARS-Quant; see Appelbaum et al., 2018).

Preregistration: This study was not preregistered.

Participants.

The final set of participants consisted of twenty-four undergraduate students (mean age = 20.2 years; 9 male, 15 female) at The Ohio State University. Since our probe task was a newly developed paradigm and there was no directly comparable previous study, we determined our sample size as follows: First, we looked at the sample sizes of previous behavioral studies that used the additional singleton paradigm with distractor probability manipulations (Failing et al., 2019; Failing & Theeuwes, 2020; Wang & Theeuwes, 2018b), which used N=24. Then, we used G*Power (Faul et al., 2007) to conduct a sensitivity analysis to similate the minimum effect sizes we could expect to detect with this sample size. For the current study, our main analysis of interest is a two-tailed t-test comparing probe accuracy in the high- vs low-probability locations.

We estimated that N=24 would allow us to detect an effect size of 0.60 or greater with 80% power, which we determined to be sufficient. One participant was replaced due to low accuracy in the search task (69.6%), which was below 3.5 SD from the group mean, and one participant was replaced because the experiment was not completed due to a technical problem. All participants reported having normal or corrected-to-normal acuity and color vision. Informed consent was obtained from all participants, and the protocols were approved by the Ohio State University Institutional Review Board.

Apparatus.

The experiment was conducted on a Mac Mini. Stimulus presentation was performed using programs written in MATLAB (The MathWorks, Natick, MA) and Psychophysics Toolbox software (Brainard, 1997). Stimuli were presented on a 24-inch Acer monitor (refresh rate = 60 Hz, resolution = 1920 x 1080). Visual angles are reported below based on a typical viewing distance of 70 cm, although head position was not fixed. Responses were made by pressing the “F” (left) and “J” (right) buttons of a keyboard with the corresponding index fingers.

Stimuli.

Both search and probe trials contained a fixation point, a search array, and a feedback display. All stimuli were presented on a black background. The search and probe stimuli were presented at an equal distance from the center (2.6° from center to fixation point; see Figure 1). A set of two colors (red [RGB: 235, 144, 172] and green [RGB: 69, 189, 170]) was used for shapes on search trials, and a white color (RGB: 255, 255, 255) was used for the bar on probe trials.

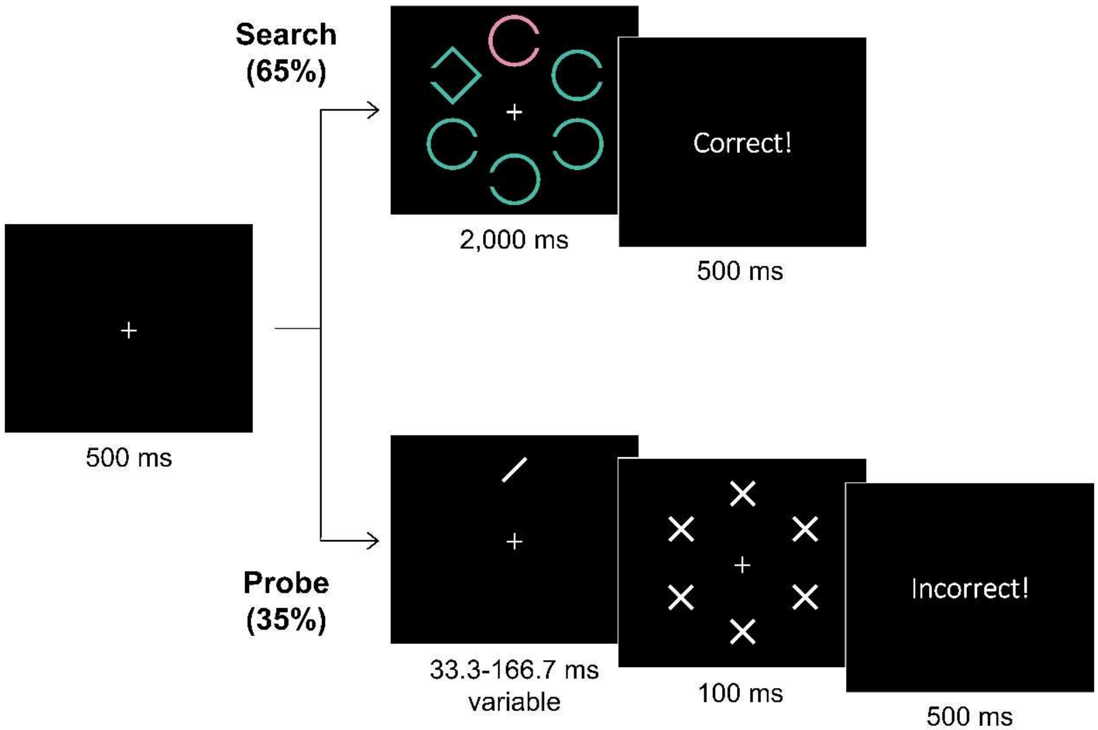

Figure 1. Example trial sequence. On search trials, displays contained six shapes, each with a gap on its left or right side. On one-third of these trials, all items were colored homogeneously (i.e., singleton-absent), and on the remaining trials, one item was drawn in a different color (i.e., singleton-present). Participants made a speeded response to the location of the gap of a target shape (an odd shape). The high-probability distractor location was fully counterbalanced across participants but was consistent within each participant. On probe trials, displays contained one bar tilted left (counterclockwise) or right (clockwise). Participants made a response about the orientation of a probe target. A probe bar could appear in the high-probability location (top location, in this example) or in a low-probability location (one of the other locations, in this example). Probe bars appeared equally often at each location. Search and probe trials were randomly interleaved.

Search displays contained either one diamond (1.3° x 1.3°) and five circles (1.3° x 1.3°) or one circle and five diamonds (stroke: 0.04°). The search target was the odd shape (a circle among diamonds or a diamond among circles). Each shape had a gap (0.26° high) located on either the left or right side of the shape.

Probe displays contained one white bar (0.78°) tilted 45° to the left or right (counterclockwise or clockwise from the vertical meridian, respectively; stroke: 0.03°). The probe bar appeared equally often at each of the six locations. A mask display which had superimposed left-tilted and right-tilted bars in all six locations followed the probe display.

Design and Procedure.

All participants were provided with written and oral descriptions of the stimuli and procedures. Participants were instructed to maintain fixation on the centrally presented fixation cross during the entire trial. The experiment began with 30 practice trials of the search task followed by 16 practice trials for the probe task. This task was the same as the one in the main experiment, except that statistical regularities of distractor locations were not yet introduced. Practice trials were excluded from the analyses reported below.

The main experiment consisted of two phases. The first phase contained 180 trials of only search trials to provide participants with the opportunity to learn the statistical regularities of distractor locations. In the second phase, participants completed 552 trials; this was comprised of 360 search trials (65%) and 192 probe trials (35%). Statistical regularities of distractor locations were manipulated on search trials throughout the entire experiment. Search and probe trials were randomly interleaved, and breaks were given every 61 trials.

On search trials, six items were presented, and participants were asked to search for the shape oddball (i.e., a circle among five diamonds or a diamond among five circles), and report whether its gap was on the left or right side by pressing a left or right button as quickly and accurately as possible. A uniquely colored singleton distractor was present on two-thirds of trials (singleton-present trials). The target shape and the singleton distractor color were randomly chosen from trial to trial respectively. One of the six locations was the high-probability location at which the singleton distractor appeared for 66.7% of the singleton-present trials, but participants were not explicitly informed of this. Singleton distractors appeared equally often at the other five locations (low-probability locations: 6.67% of trials each). The high-probability location remained the same for each participant and was counterbalanced across participants. The target appeared equally often at each of the six locations on both singleton-absent and singleton-present trials. This probability manipulation is identical to that of previous studies (Failing et al., 2019; Huang et al., 2021; Wang, van Driel, et al., 2019). The search array appeared until response, but if participants did not respond by 2,000 ms, a time-out display appeared with the text "Too Slow" for 500 ms. A feedback display followed responses, for 500 ms. Feedback consisted of the word "Correct!" or "Incorrect!" displayed in the middle of the screen.

On probe trials, a white bar was presented, and participants were asked to report whether the bar was left-tilted or right-titled by pressing the left or right button as accurately as possible. The probe bar was presented at each of the six locations equally often. The probe display appeared for a variable duration that was adjusted adaptively, and it was followed by a 100-ms mask of superimposed left-tilted and right-titled bars. The probe bar was initially presented for 100 ms, and at each break (every 61 trials), the probe exposure duration was adjusted up or down by one refresh rate (16.7 ms; i.e., add or subtract 16.7 ms) if accuracy fell below 65% or above 85%, respectively (see Leber et al., 2016). It should be noted that this procedure was implemented to adjust the overall accuracy level and not the differences between conditions; that is, our main comparison of interest (the difference between the high-probability and low-probability conditions) remained orthogonal to the titrated overall accuracy.

Critically, both search and probe trials began with the presentation of a blank screen for 500 ms followed by a fixation screen for 500 ms, meaning that participants had no foreknowledge about an upcoming trial until they saw the display.

Data Analysis.

All analyses were conducted in JASP (JASP Team, 2022, Version 0.16.3). The partial-eta squared or Cohen's *d* [*d* = (mean 1 – mean 2) / SD-pooled] was used to measure effect sizes. We also computed Bayes Factors to assess the degree of evidence supporting our critical hypothesis on probe trials. For all Bayesian analyses, we used the default prior (Cauchy) in JASP. We used the default because we did not have a clear justification to use an informed prior.

Results

Search-task

Mean accuracy on search trials was 95.3%. For all RT analyses, we followed a priori criteria to exclude trials with responses faster than 50 ms as well as incorrect trials. Based on a modified recursive trimming procedure (Van Selst & Jolicoeur, 1994), reaction times 3.5 standard deviations above or below the mean for each participant were subsequently removed. Altogether, this resulted in the elimination of 6.4% of all search trials.

Attentional capture effects

RT. Figure 2A shows the mean differences in RT among distractor conditions on search trials[2]. To examine whether there was reduced attentional capture when a distractor appeared at the high-probability location, a repeated-measures ANOVA was performed on mean RTs with the distractor condition (singleton-absent, high-probability, and low-probability) as a factor. The

[2] As mentioned in the main text, the first phase only had search trials, and the second phase had intermixed search and probe trials. The pattern of results remained the same when we excluded the first phase (search-only trials), therefore, we collapsed search data including the first phase.

main effect of distractor condition was significant, $F(2, 46) = 89.730$, $p < .001$, $\eta_p^2 = .796$. Pairwise comparisons revealed that responses were faster on singleton-absent trials (M = 797 ms) than on both high-probability (M = 866 ms), $t(23) = 7.603$, $p_{HB} < .001$, $d = 0.482$, and low-probability trials (M = 918 ms), $t(23) = 13.353$, $p_{HB} < .001$, $d = 0.847$. More importantly, responses were faster on high-probability trials than on low-probability trials, $t(23) = 5.750$, $p_{HB} < .001$, $d = 0.365$, showing a reduced attentional capture in the high-probability location and replicating the previous findings (Failing et al., 2019; Huang et al., 2021; Kong et al., 2020; Wang & Theeuwes, 2018a, 2018b).

To further test the spatial distribution of the observed effect (see Figure 2B), the data from low-probability locations on singleton-present trials were divided into three groups depending on the distance between a singleton distractor and the high-probability distractor location. A repeated-measures ANOVA was performed on mean RTs with the distance from the high-probability distractor location (close, middle, and far) as a factor. The results showed that RTs did not differ significantly depending on the distance from the high-probability location, $F(2, 46) = 0.387$, $p = .681$, $\eta_p^2 = .017$, revealing that the capture effect did not vary with distance.

Accuracy. As we did with RT data, we first performed a repeated-measures ANOVA on mean accuracy rates. The results conform to the results from RT data. The main effect of distractor condition was significant, $F(2, 46) = 40.525$, $p < .001$, $\eta_p^2 = .638$. Pairwise comparisons revealed that responses were more accurate on singleton-absent trials (M = 98%) than on both high-probability (M = 95%), $t(23) = 3.365$, $p_{HB} = .002$, $d = 0.647$, and low-probability (M = 92%), $t(23) = 8.914$, $p_{HB} < .001$, $d = 1.714$, trials. Responses were more accurate on high-probability trials than on low-probability trials, $t(23) = 5.549$, $p_{HB} < .001$, $d = 1.067$.

Next, as we did with RT data, we ran a repeated-measures ANOVA across three low-probability locations (close, middle, and far). The results showed that RTs did not differ significantly depending on the distance from the high-probability location, $F(2, 46) = 0.676$, $p = .514$, $\eta_p^2 = .029$.

Target processing

RT. To look at the data from a different angle, we tested whether target processing was impaired in the high-probability location by examining RTs in the singleton-absent condition. Responses were slower when the target was presented at the high-probability distractor location (M = 820 ms) than at low-probability distractor locations (M = 792 ms), $t(23) = 3.264$, $p = .003$, $d = 0.666$.

To further test the spatial distribution of the target slowing effect, the data from low-probability locations on singleton-absent trials were divided into three groups depending on the distance between a target and the high-probability distractor location. A repeated-measures ANOVA was performed on mean RTs with the distance from the high-probability distractor location (close [M = 807 ms], middle [M = 785 ms], and far [M = 776 ms]) as a factor. The results showed that target processing in low-probability locations differed significantly depending on the distance from the high-probability location, $F(2, 46) = 3.296$, $p = .046$, $\eta_p^2 = .125$. Pairwise comparisons showed that responses were significantly slower when a target appeared in the close location than in the far location, $t(23) = 2.505$, $p_{HB} = .048$, $d = 0.227$. All other comparisons did not reach significance, $ps > .1$.

Accuracy. As we did with RT data, we first performed a repeated-measures ANOVA on mean accuracy rates. Accuracy rates did not differ between the high-probability and low-probability locations, $t(23) = 0.605$, $p = .551$, $d = 0.124$.

Next, as we did with RT data, we ran a repeated-measures ANOVA across three low-probability locations (close, middle, and far). The results showed that RTs did not differ significantly depending on the distance from the high-probability location, $F(2, 46) = 1.616$, $p = .210$, $\eta_p^2 = .066$.

Probe-task

The probe was presented for a mean of 105 ms across all blocks and participants (range of participant means: 60 ms to 153 ms). Trials with reaction times faster than 50 ms or slower than 5,000 ms were removed on a priori basis, which accounted for 0.2% of probe trials.

To test whether there was a difference in probe accuracy between the high-probability and low-probability locations, accuracy for the bar location (high-probability location vs. low-probability location) was compared, showing no significant difference, $t(23) = 0.216$, $p = .831$, $d = 0.044$, $BF_{01} = 4.560$ (see Figure 2C). There was no significant difference in RT data as well, $t(23) = 0.110$, $p = .913$, $d = 0.022$.

To further test the spatial distribution, a repeated-measures ANOVA was conducted on mean accuracy rates for low-probability locations with the distance from the high-probability location (close, middle, and far) as a factor. Accuracy rates did not vary depending on distance (see Figure 2D), $F(2, 46) = 0.576$, $p = .566$, $\eta_p^2 = .024$. RTs did not differ depending on distance as well, $F(2, 46) = 0.520$, $p = .598$, $\eta_p^2 = .022$.

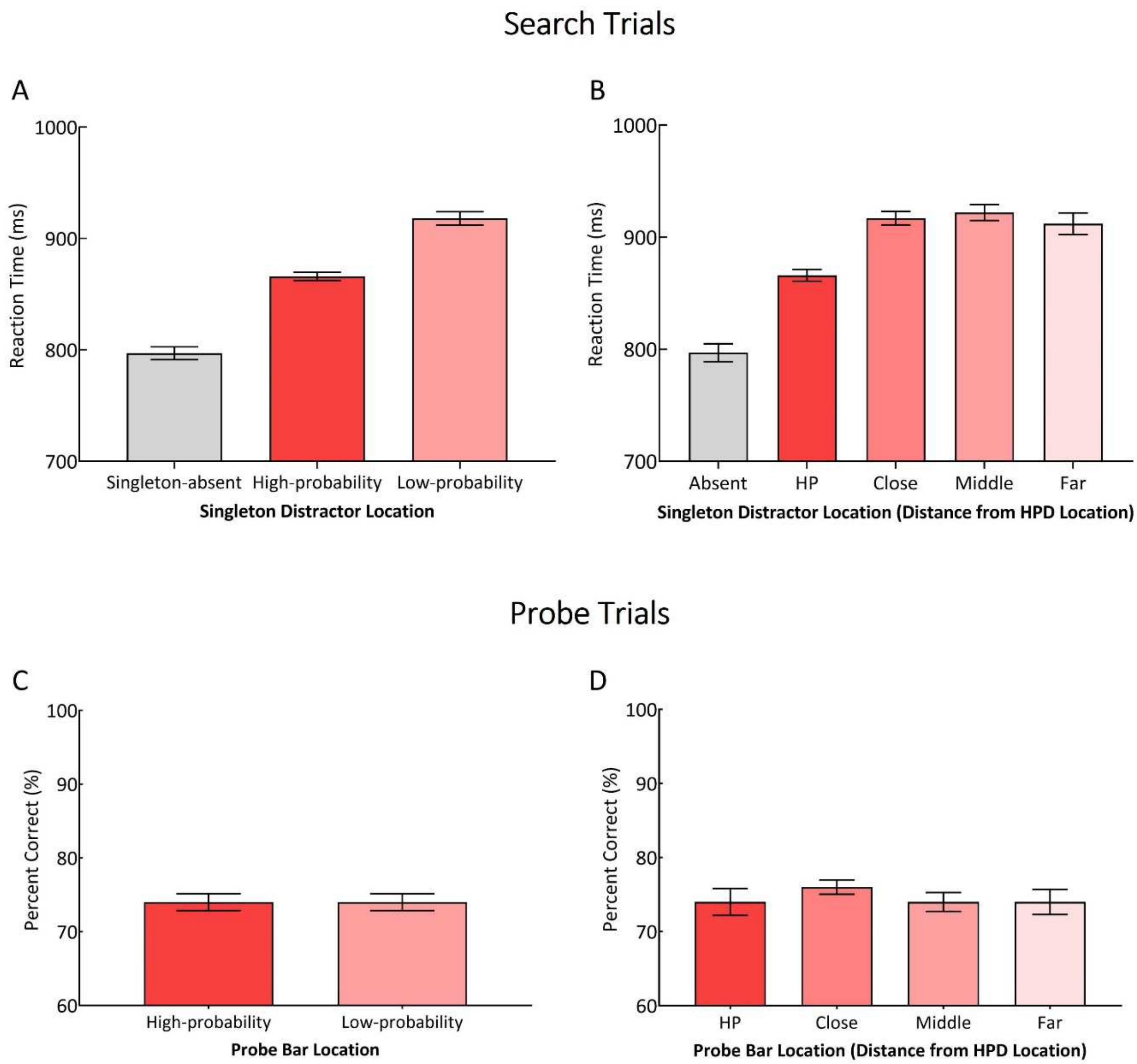

Figure 2. Results from Experiment 1. A and B show the data from search trials, and C and D show the data from probe trials. (A) RTs on search trials as a function of singleton distractor location. (B) RTs on search trials as a function of singleton distractor location relative to the high-probability distractor location. (C) Accuracy rates on probe trials as a function of probe bar location. (D) Accuracy rates on probe trials as a function of probe bar location relative to the high-probability distractor location. Error bars represent the within-subject SEM, corrected for within-subject designs (Cousineau, 2005).

Discussion

In Experiment 1, we replicated Wang and Theeuwes' (2018b) finding on search trials, showing that responses were faster when a salient distractor appeared in the high-probability location than in low-probability locations. However, on probe trials we found no difference in probe target report between the high- and low-probability conditions, implying that attention was evenly distributed across locations at the time of display onset and that spatial suppression may have been neither proactive nor reactive. These findings seem consistent with neither the proactive nor reactive accounts of suppression. Rather, they fit with decision/response-level effects, such as differential disengagement and decision-related slowing during search, which cannot manifest during the data-limited probe trials.

While decision/response-level effects may provide a contributing factor, we are cautious to conclude that they fully explain previous findings on search trials. Notably, the absence of a distance effect on search trials suggests that suppression may not have been as strong as it was in previous studies that have reported the distance effect (Wang & Theeuwes, 2018a, 2018b). Thus, before reaching firm conclusions, we first seek to strengthen suppression. There could be many different ways to maximize suppression, but one possible reason why it may have been weak is because the search target sometimes appeared in the high-probability distractor location. That is, the task-relevance of distractor locations may prevent the distractor from being completely suppressed (see Rule 1 of Wöstmann et al., 2022), and perhaps that limited our ability to detect proactive or reactive suppression on the probe task. To achieve maximal suppression, salient distractors should be antipredictive of a target location (Adams et al., 2022). Therefore, in Experiment 2 we switched to a design where a target never appeared in the high-probability distractor location.

Experiment 2

On search trials of Experiment 2 a target never appeared in a high-probability location on both singleton-absent and singleton-present trials. The probe task was identical to that used in Experiment 1.

Method

Participants.

We sought the same sample size in this study as in Experiment 1. Once again, the final set of participants consisted of twenty-four undergraduate students (mean age = 19.5 years; 12 male, 11 female, 1 non-binary) at The Ohio State University. Four participants were replaced due to low accuracy in the search task (70.7%, 48.7%, 77.8%, and 50.7%), which was below 3.5 SD from the group mean, one participant was replaced because they withdrew in the middle of experiment due to eye pain, and one participant was replaced because the experiment was not completed due to a technical problem. All participants reported having normal or corrected-to-normal acuity and color vision. Informed consent was obtained from all participants, and the protocols were approved by the Ohio State University Institutional Review Board.

Apparatus, Stimuli, Design, and Procedure.

The apparatus, stimuli, design, and procedure were identical to those used in Experiment 1, except that a target never appeared in the high-probability location on both singleton-absent and singleton-present trials of search trials. A target appeared at the other locations equally often. On probe trials, a probe bar appeared at each location equally often, and the probe display appeared for a variable duration that was adjusted adaptively, as in Experiment 1.

Results

Search-task

Mean accuracy was 95.2%. Outlier latencies were eliminated as in Experiment 1, resulting in the elimination of 6.1% of all search trials.

Attentional capture effects

RT. Figure 3A shows the mean differences in RT among distractor conditions[3]. To examine whether there was reduced attentional capture when a salient distractor appeared at the high-probability location, a repeated-measures ANOVA was performed on mean RTs with the distractor condition (singleton-absent, high-probability, and low-probability) as a factor. The main effect of distractor condition was significant, $F(2, 46) = 129.712$, $p < .001$, $\eta_p^2 = .849$. Pairwise comparisons revealed that responses were faster on singleton-absent trials ($M = 795$ ms) than on both high-probability trials ($M = 869$ ms), $t(23) = 8.986$, $p_{HB} < .001$, $d = 0.571$, and low-probability trials ($M = 927$ ms), $t(23) = 16.069$, $p_{HB} < .001$, $d = 1.022$. More importantly, responses were faster on high-probability trials than on low-probability trials, $t(23) = 7.083$, $p_{HB} < .001$, $d = 0.450$, showing showing a reduced attentional capture in the high-probability location.

To further test the spatial distribution, the data from low-probability locations on singleton-present trials were divided into three groups depending on the distance between a singleton distractor and the high-probability location (see Figure 3B). A repeated-measures ANOVA was performed on mean RTs with the distance (close, middle, and far) as a factor. The results showed that RTs differed significantly depending on the distance from the high-probability location, $F(2, 46) = 10.525$, $p < .001$, $\eta_p^2 = .314$, revealing a spatial gradient. Pairwise comparisons showed that responses were significantly faster when a singleton distractor appeared in the close location ($M = 898$ ms) than in the middle ($M = 945$ ms), $t(23) = 3.735$, p_{HB}

[3] As mentioned in the main text, the first phase only had search trials. The pattern of results remained the same when we excluded the first phase (search-only trials), therefore, we collapsed search data including the first phase.

= .001, *d* = 0.316 and far (*M* = 950 ms), $t(23) = 4.175$, $p_{HB} < .001$, $d = 0.353$, locations. The middle and far locations were not significantly different, $p_{HB} = .662$, $d = 0.037$.

Accuracy. As we did with RT data, we first performed a repeated-measures ANOVA on mean accuracy rates. The results conform to the results from RT data. The main effect of distractor condition was significant, $F(2, 46) = 47.738$, $p < .001$, $\eta_p^2 = .675$. Pairwise comparisons revealed that responses were more accurate on singleton-absent trials (*M* = 97%) than on low-probability (*M* = 91%) trials, $t(23) = 9.260$, $p_{HB} < .001$, $d = 1.454$. Responses were more accurate on high-probability trials (*M* = 96%) than on low-probability trials, $t(23) = 7.331$, $p_{HB} < .001$, $d = 1.151$. Singleton-absent and high-probability trials were not significantly different, $t(23) = 1.929$, $p_{HB} = .180$, $d = 0.303$.

Next, as we did with RT data, we ran a repeated-measures ANOVA across three low-probability locations (close, middle, and far). The results showed that accuracy rates did not differ significantly depending on the distance from the high-probability location, $F(2, 46) = 2.276$, $p = .114$, $\eta_p^2 = .09$.

Target processing

Although targets never appeared in the high-probability location in Experiment 2, to test the spatial distribution, the data from singleton-absent trials were divided into three groups depending on the distance between a target and the high-probability distractor location. A repeated-measures ANOVA was performed on mean RTs with the distance (close, middle, and far) as a factor, showing that target processing did not differ significantly depending on the distance from the high-probability location, $F(2, 46) = 1.266$, $p = .292$, $\eta_p^2 = .052$.

There was no effect on accuracy rates, $F(2, 46) = 0.469$, $p = .628$, $\eta_p^2 = .02$.

<u>Probe-task</u>

The probe was presented for a mean of 113 ms across all blocks and participants (range of participant means: 57 ms to 151 ms). As in Experiment 1, outlier responses were removed on a priori basis, which accounted for 0.2% of probe trials.

To test whether there was a difference in probe accuracy between the high-probability and low-probability locations, accuracy for the bar location (high-probability location vs. low-probability location) was compared, showing that responses were significantly different between high-probability and low-probability locations, $t(23) = 3.568$, $p = .002$, $d = 0.728$, $BF_{10} = 22.84$ (see Figure 3C). Responses were more accurate when a probe bar was presented in the high-probability location (M = 74%) than in low-probability locations (M = 69%). There was no significant difference in RT data, $t(23) = 1.396$, $p = .176$, $d = 0.285$.

To further test the spatial distribution, a repeated-measures ANOVA was conducted on mean accuracy rates for low-probability locations with the distance from the high-probability location (close, middle, and far) as a factor. Accuracy rates among these low-probability locations did not vary significantly depending on distance (see Figure 3D), $F(2, 46) = 1.369$, $p = .265$, $\eta_p^2 = .056$.

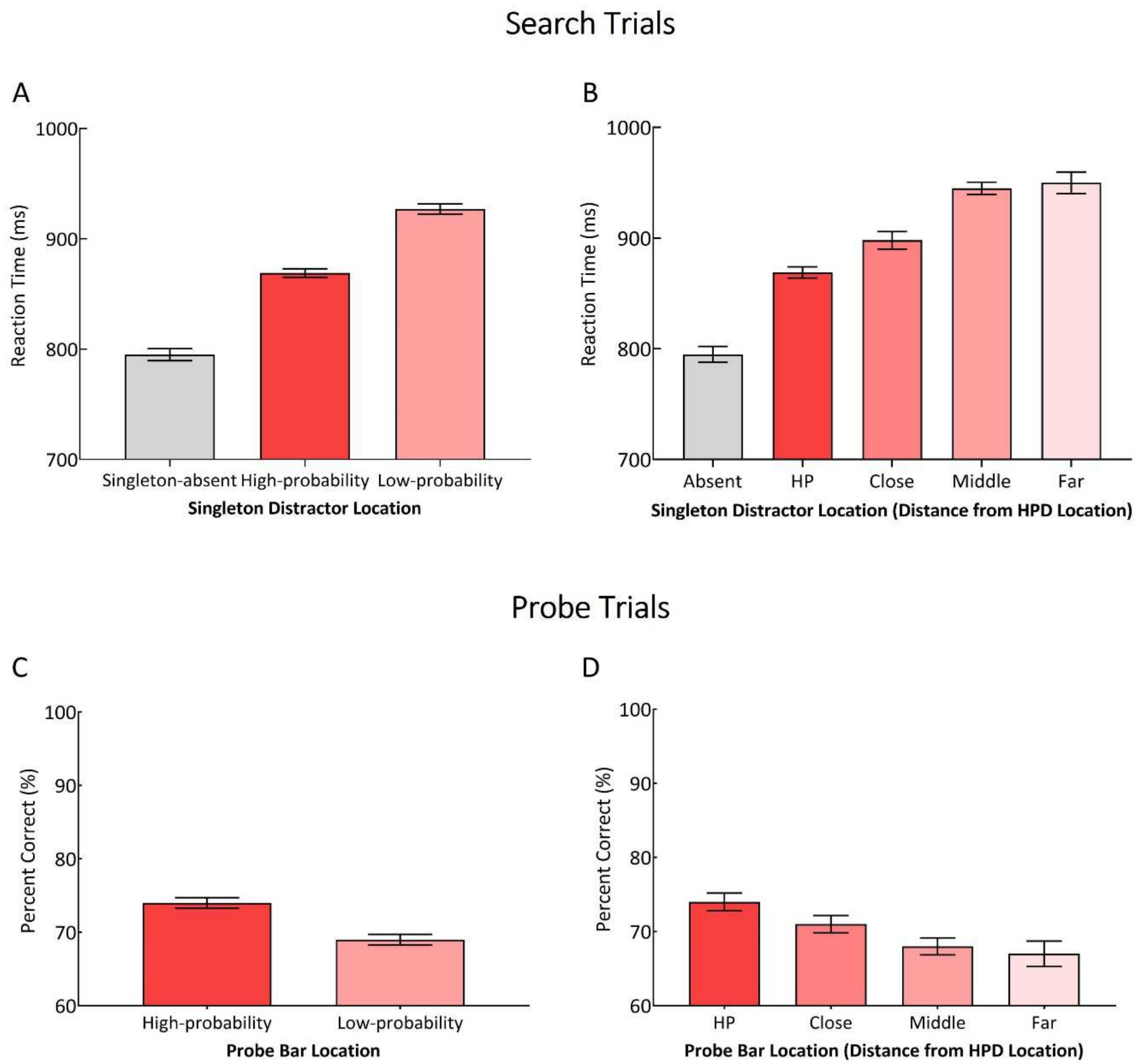

Figure 3. Results from Experiment 2. A and B show the data from search trials, and C and D show the data from probe trials. (A) RTs on search trials as a function of singleton distractor location. (B) RTs on search trials as a function of singleton distractor location relative to the high-probability distractor location. (C) Accuracy rates on probe trials as a function of probe bar location. (D) Accuracy rates on probe trials as a function of probe bar location relative to the high-probability distractor location. Error bars represent the within-subject SEM, corrected for within-subject designs (Cousineau, 2005).

Discussion

In Experiment 2, when a target never appeared in the high-probability location, incentivizing maximal suppression, we found a significant signature of suppression on search trials. The suppression effect at low-probability locations varied with distance from the high-probability location (which we did not observe in Experiment 1), suggesting that suppression was more robust in Experiment 2 than in Experiment 1. More importantly, on probe trials we found enhanced performance in the high-probability location; responses to the probe bar were more accurate when it appeared in the high-probability location than in low-probability locations, suggesting that participants adopted a reactive strategy, initially selecting the high-probability location prior to suppressing it.

General Discussion

Across two experiments, the current study provides a demonstration of spatial suppression through statistical learning that did not occur proactively and indeed appeared to occur reactively when suppression was strongly implemented. In Experiment 1, we found no evidence for proactive suppression; probe detection accuracy did not differ between the high- and low-probability locations on probe trials. The probe data suggest that attention was distributed evenly across locations at the moment search stimuli would have been presented. In Experiment 2, when suppression was more incentivized on search trials, probe trials showed higher probe detection accuracy in the high-probability location than in low-probability locations.

Reactive suppression was evident from the search and probe data of Experiment 2, with search RTs showing a signature of suppression and probe accuracy revealing enhancement at the moment search would have begun. Moreover, on search trials, despite evidence of spatial suppression, we also observed a persistent distractor cost on trials where the distractor appeared in the high-probability location (i.e., although attentional capture was mitigated in the high-probability condition relative to the low-probability condition, responses to a target in the high-probability condition were still slower than in the singleton-absent condition). This significant distractor cost reveals that the suppression of the high-probability location was not absolute but rather did incur some processing, consistent with a reactive account.

The present accuracy probe method allowed us to carry out a clean test of proactive vs. reactive mechanisms without the contamination of decision/response-level effects that may be present in RT data, such as differential disengagement and decision-related slowing. Experiment 1 especially highlights the issue; when we did not see evidence of any suppression – proactive or reactive – from the accuracy probe task (perhaps due to weak suppression), we still saw reduced RT capture from distractors and slowed responses to the search target at the high probability location. These findings are consistent with differential disengagement and decision-related slowing, respectively. It is also possible that these effects were present in Experiment 2 as well as previous studies with this paradigm. Indeed, previous studies have found more direct evidence for differential disengagement, showing that fixations on the distractor were shorter when it appeared at the high-probability location than at the low-probability location (Sauter et al., 2021; Wang, Samara, et al., 2019). Other work has characterized the existence of inhibitory processes at the decision/response level (Carmel & Lamy, 2014; Darnell & Lamy, 2021).

The eye-tracking study of Wang, Samara, et al. (2019) seems to contradict our finding on probe trials: the authors showed that fewer saccades landed on the distractor location when the distractor appeared at the high-probability location than at a low-probability location (see also Di Caro et al., 2019). However, the mean latency of saccades was around 240 ms which is slower than previous studies of oculomotor capture (e.g., Theeuwes et al., 2003: 209 ms). It may be possible that a reactive mechanism can describe these data: covert attention is moved to the high-probability location, but participants strategically delay the launching of the saccade to avoid the costs of oculomotor capture. Previous work has shown that effects of oculomotor capture are reduced with slower saccadic latencies (van Zoest et al., 2004). In fact, Sauter et al. (2021) showed that saccades to distractors in the high-probability location had slightly longer latencies, which could also be consistent with oculomotor avoidance.

It is important to emphasize that the main contribution of our results is that RT signatures of suppression (as observed on search trials) cannot safely be assumed to reflect proactive suppression. To be clear, we are not arguing that it is impossible to obtain proactive suppression in all cases. For instance, Wang, van Driel, et al. (2019) collected electrophysiological measures and argued for the existence of proactive suppression based on alpha-band and distractor positivity (P_D) signatures. It is also possible that other types of tasks (e.g. search tasks promoting a feature-search mode [Bacon & Egeth, 1994]) could result in more proactive suppression.

Moreover, proactive suppression can be defined in multiple ways. The way we have defined it stipulates that it occurs when the priority signal at a specific location is suppressed *before* a stimulus is presented (Theeuwes et al., 2022). However, one can conceive of proactive suppression occurring *after* a stimulus is presented but before the first shift of attention (Gaspelin & Luck, 2018b; Sawaki & Luck, 2010). As we discussed earlier, some studies using placeholders have reported evidence of proactive suppression (Huang et al., 2021, 2022; Leber et al., 2016). In such studies, it is important to determine whether suppression is achieved prior to the first attentional shift or if a reactive mechanism is involved, in which the placeholder in a to-be-ignored location is first attended and then disengaged from.

Importantly, while we used the former definition of proactive suppression (i.e., suppression occurs before stimulus onset), our interpretation of the current findings should hold for both definitions. That is, in Experiment 2, we found *enhanced* accuracy at the high-probability location on the probe task, which is evidence of an attentional shift to the high-probability location, a finding that is incompatible with either definition of proactive suppression. The present results suggest that spatial suppression caused by a salient distractor frequently appearing in one location cannot safely be assumed to be proactive. We produce evidence that indeed, robust suppression was supported by a reactive mechanism; observers initially select a to-be-ignored location prior to suppression.

Overall, these data invite a reinterpretation of how learned spatial suppression might take place. It is tempting to assume that individuals consistently suppress a learned distractor location throughout the experimental session (or a consistently distracting location in daily life). However, it may instead be the case that individuals do not alter their spatial distribution of attention but instead anticipate where a distractor will appear so that they can rapidly handle it.

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