Experience-driven suppression of irrelevant distractor locations is context dependent

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Author Note

Data from Experiments 1, 2, 3 (N=34 out of 51), and Supplementary Experiment A were presented at the 2019 meeting of the Psychonomic Society (Allon & Leber, 2019).

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Abstract

Humans can learn to attentionally suppress salient, irrelevant information when it consistently appears at a predictable location. While this ability confers behavioral benefits by reducing distraction, the full scope of its utility is unknown. As people locomote and/or shift between task contexts, known-to-be-irrelevant locations may change from moment to moment. Here we assessed a context-dependent account of learned suppression: can individuals flexibly update the locations they suppress, from trial to trial, as a function of task context? Participants searched for a shape target in displays that sometimes contained a salient, irrelevant color singleton distractor. When one scene category was presented in the background (e.g., forests), the distractor had a greater probability of appearing in one display location than the others; for another scene category (e.g., cities), we used a different high-probability location. Results in Experiments 1 and 2 (and in supplemental data) failed to show any context-dependent suppression effects, consistent with earlier work. However, in Experiments 3 and 4, we reinforced the separation between task contexts by using distinct sets of shape and color stimuli as well as distinct kinds of reported features (line orientation vs. gap judgment). Results now showed robust task-dependent signatures of learned spatial suppression and did not appear to be tied to explicit awareness of the relationship between context and high-probability distractor location. Overall, these results reveal a mechanism of learned spatial suppression

that is flexible and sensitive to task contexts, albeit one that requires sufficient processing of these contexts.

Significance Statement

Our visual environments contain an enormous quantity of information, only some of which is relevant to our task at hand. It is thus imperative to ignore the irrelevant information, and humans are equipped with many tools to do so. One such tool, spatial suppression, allows people to ignore locations in space that are known to contain frequently distracting information. But, in the real world, what is considered distracting may change from moment to moment as we switch between task contexts. Can people flexibly update the locations they suppress as they switch between task contexts? Here, we provide critical evidence that context-dependent suppression does indeed occur. These results shed light on how people are able to avoid distraction in the real world.

Experience-driven suppression of irrelevant distractor locations is context dependent

Our sensory systems constantly collect a great abundance of information, but we are severely limited in our capacity to process this information, and it is thus vital that we prioritize relevant information while ignoring irrelevant information. But how do we choose which information to prioritize? The mechanisms of attention offer several routes to prioritization. First, stimulus-driven attention prioritizes sensory information that is perceptually salient, by virtue of its physical properties, such as uniqueness, brightness, or size (Jonides, 1981; Theeuwes, 1992; Yantis, 1993). Second, goal-driven attention prioritizes information based on the observer's intention (Corbetta & Shulman, 2002; Folk et al., 1992; Posner et al., 1978). Third, experience-driven attention prioritizes information based on learning or recent experience (Chun & Jiang, 1998; Leber & Egeth, 2006; Miller, 1988; see Awh et al., 2012 for a theoretical review).

The experience-driven component has been the target of intensive research in the past few decades, with a particular emphasis on how learning interacts with attention. Various phenomena documenting this interaction include contextual cueing (Chun & Jiang, 1998), location probability learning (Geng & Behrmann, 2002; Jiang et al., 2013; Miller, 1988), visual statistical learning (Fiser & Aslin, 2001; Turk-Browne et al., 2005), value-based learning (Anderson et al., 2011; Libera & Chelazzi, 2006), and learned suppression (Goschy et al., 2014; Kelley & Yantis, 2009; Reder et al., 2003; Wang & Theeuwes, 2018a).

As the study of experience-driven attention has matured, researchers have been able to move from simply documenting experience-driven effects to questioning the mechanisms underlying these effects. In this paper, we contrast two competing theoretical accounts of experience-driven learning. On the one hand, a *context-invariant* account determines the attentional priority of a feature or location based purely on its recent history. The more times one selects a specific feature or spatial location, the more it will be prioritized for future attentional shifts; likewise, the more one rejects a feature or location, the less it will be prioritized for future attentional shifts. No consideration of task context is given. In contrast, a *context-dependent* account stipulates that the prioritization of a feature or location is conditioned upon the behavioral context in which it is learned.

Whether a learning phenomenon is context-dependent carries important implications for its underlying mechanism. For example, in the perceptual learning domain, in which hours of practice lead to visual performance improvements, effects that are largely specific to practiced features and retinal locations are linked to neuronal alterations in early visual cortex; however, transfer across locations and features provides evidence for more mid- and high-level influences on learning (Ahissar & Hochstein, 1997; Dosher et al., 2013; Fahle, 2005).

Several forms of experience-driven attention have been shown to be context dependent. Contextual cueing may be the most direct example, by which spatial locations are prioritized solely on the basis of the spatial arrangement of the non-target display items (Chun & Jiang, 1998). Additional demonstrations have been provided for the learning of attentional strategy (Cosman & Vecera, 2013; but see Cochrane & Pratt, 2021), value-driven attentional learning (Anderson, 2015), target-distractor congruency effects (Crump et al., 2018), and spatial suppression (Leber et al., 2016).

In this paper, we take a closer look at learned spatial suppression. It has previously been shown that, when salient, irrelevant distractors are presented more frequently at one high-probability display location than others, interference effects are reduced compared to other, low-probability locations (Goschy et al., 2014; Kelley & Yantis, 2009; Narhi-Martinez et al., 2024; Reder et al., 2003; Wang & Theeuwes, 2018a). In one paradigm that has become widely used in recent years, Wang & Theeuwes (2018a) modified the classic “additional singleton” paradigm (Theeuwes, 1992), presenting salient, irrelevant color singleton distractors in one location on 65% of the trials, while equally distributing the distractor in the other 7 display locations on the remaining 35% of trials. Results showed significantly faster response times (RT) when distractors appeared in the high probability vs. low probability locations.

Are such learning effects context-dependent? Context invariance would suggest a low-level instantiation of the learning effect, in which a spatial priority map is altered in a durable, or persistent, fashion (for discussion, see Britton & Anderson, 2020; Leber, 2021). By this account, learned suppression should be wholly predicted by the sum of accumulated rejections of the distractor location in each location of the display. Locations containing more cumulative rejections should be more suppressed. Context dependency, however, would suggest higher level control of the suppression mechanism. Instead of purely summing the accumulation of rejections in each location, suppression is determined by the accumulation of distractor rejections at each location within each context. Thus, suppression is determined in a context-dependent fashion.

Leber et al., (2016) offered initial evidence for context-dependent suppression. Participants were provided with a 70%-valid cue that predicted the target location in a 4-item search array. Unbeknownst to participants, the cue also predicted the location of a salient distractor with 70% validity. Results showed that validly cued distractors produced smaller signatures of distraction than invalidly cued distractors. Note that while these results demonstrate context-dependent distractor rejection, the study left unanswered questions about the conditions under which such rejection can occur. Specifically, because the target and distractor locations were cued together and covaried, the results cannot address whether distractor rejection can be learned independently from target selection.

Additional research has attempted to establish context dependency within the paradigm of Wang and Theeuwes (2018a). Their paradigm provides a straightforward method to assess distractor rejection independent of target selection, as there are no statistical associations between target and distractor locations. Borrowing a context manipulation introduced by Cosman and Vecera (2013), Britton and Anderson (2020, Experiment 1), superimposed search displays on background scenes that were used to form two distinct contexts, which were paired with high-probability distractor locations. For example, for one participant, forest scenes could predict one high probability distractor location, while city scenes could predict another. Results showed no difference in RT for distractors as a function of background scene, thus failing to establish context dependency. However, a subsequent experiment provided an important nuance to the study. Britton and Anderson (2020, Experiment 3) used the basic Wang and Theeuwes (2018a) manipulation for a training phase of trials and then transferred participants to a test phase in which the search task stimuli and response rules were changed. Additionally, the distractor became equiprobable across all display locations, so that the authors could measure the time-course of learning extinction. Results showed no evidence that spatial suppression persisted into the test phase, despite previous data showing robust persistence when the task stimuli were unchanged (Britton & Anderson, 2020, Experiment 2). Thus, while not directly showing context-dependent suppression, the results refute a strong case of context invariance in learned spatial suppression.

Subsequent work by De Waard et al., (2022) also attempted to find evidence for context dependency. Using logic similar to Britton and Anderson (2020), across three experiments, they paired background color, auditory cues, and task rules, respectively, with high probability distractor locations. Results were generally consistent with the context invariant account, as high probability distractors equally affected RT regardless of context. However, one notable exception was found in the third experiment, when the researchers paired response rules with distractor locations (i.e., participants were cued to report the target orientation using either 'Z' and 'C' keys or the left and right arrow keys). Here, the participants who reported being aware of the context manipulation did successfully modulate their degree of ignoring high probability distractors depending on context. The authors concluded that, provided observers are unaware of the manipulation, distractor rejection is inflexible to context variation.

To summarize, the evidence for context dependency versus invariance has been mixed. In this study, we report a series of experiments that we ran in parallel with the studies of Britton and Anderson (2020) and De Waard et al., (2022). Our approach has several thematic similarities with these two papers. In Experiments 1, 2, and Supplementary Experiment A, we paired two sets of background scenes – city and forest – with high probability distractor locations. Like Britton & Anderson (2020), who used a similar approach, we failed to find consistent evidence for context-dependent suppression. We then speculated that, since the background scenes were entirely irrelevant to the task requirements, they may have been ignored. Previous implicit learning research has emphasized the importance of attention to statistical regularities (Jiang & Chun, 2001; Turk-Browne et al., 2005); therefore, in Experiments 4 and 5, we explicitly linked the background scene to the tasks. We paired each background scene type with the search task shapes, colors, and reported target features (line orientation or gap); note, however, that while participants now needed to attend the background and/or task stimuli to know which target feature to report, we did not inform them that the distractor locations were correlated with these task characteristics. These latter two experiments provided robust evidence for context-dependent suppression. While these results are similar to the aware participants of De Waard et al. (2022), our results suggest that awareness was not required for the learning effect to emerge. The main conclusion we draw from this work is that context-dependent suppression may be learned incidentally, but such learning is not compulsory; observers must attend the relevant environmental cue, and sufficient reinforcement of the separation between task contexts is required.

Experiment 1

This was our first attempt to observe context-dependent suppression in the Wang & Theeuwes (2018a) paradigm, in which we borrowed the background scene manipulation of Cosman and Vecera (2013; see also Britton & Anderson, 2020). On each trial, we presented one of 3 city or 3 forest scenes in the background. Each scene category predicted a distinct high-probability distractor location, and our goal was to determine if participants learned to ignore the distractors in a context-dependent or context-invariant fashion. The raw data files of participants included in the analysis were uploaded to the Open Science Foundation platform (https://osf.io/qys95/).

Method

Participants. Twenty-eight students from The Ohio State University (23 women, 5 men, *M* = 19.21 years, *SD* = 2.96) participated in a 90-minute experimental session in exchange for course credit. Participants in all experiments gave their informed consent, and all protocols were approved by the Behavioral and Social Sciences Institutional Review Board at The Ohio State University. Participants in all experiments had self-reported normal or corrected-to-normal visual acuity and color-vision. Five participants were excluded from the analysis due to either not finishing the experiment (3 participants), having error rates in the High-probability (HP) or Low-probability (LP) that were more than 2.5 *SD* of the group (0 participants), or having more than 15% of trials removed in one of the HP, LP, or no-distractor conditions because RTs were less than 100 ms or more than 3 *SD* above the participant's mean (2 participants). Therefore, data reported in the Results section was analyzed from the remaining 23 participants.

Apparatus*.* Stimuli were presented on a 24-inch LCD monitor with a 60 Hz refresh rate, at 1920 × 1080 resolution. Participants were seated approximately 56 cm from the monitor. The same apparatus was used in all experiments.

Stimuli and Procedure. ***Visual Search Task.*** We used a visual search task similar to the one used in Wang and Theeuwes (2018a, 2018b, 2018c), embedded on top of city or forest scenes that constituted the task-irrelevant contextual information. The scenes were similar to the ones used in Cosman and Vecera (2013), with equal probability for each category scene (i.e., city or forest) in every trial. Each trial started with a 1500 milliseconds (ms) display of a city scene or a forest scene presented on the entire screen. The scene remained on the screen throughout the trial. There were 3 possible scenes for each category, and the scene for each trial was randomly chosen from the scenes of the category for that trial with equal probability. Then, a white fixation cross ("+": 0.63° height and width) was presented in the middle of the screen on top of a black square for 500 milliseconds (ms) and remained visible throughout the trial. The black square subtended 13.4° visual angle in height and width, and was followed by the search array appearing on top of the black square and remaining until a response was omitted. Participants had to search for the *odd shape* which was the target (i.e., a circle or a diamond) among five items with a different shape which were the distractors (i.e., diamonds when the target was a circle and circles when the target was a diamond), and indicate as quickly as possible whether the orientation of a line segment inside the odd shape was vertical or horizontal (with equal probability) by pressing the *up* or the *left* key on the keyboard. Diamonds subtended 2.63° in height and width, circles subtended 2.42° in diameter, and line segments subtended 0.52° in length; all stimuli had a stroke of 0.13°. The line segment also appeared inside each of the distractors, with the orientation randomly determined for each distractor. The items in the search display appeared in either green (RGB: 0, 255, 0) or red (255, 0, 0) color, with equal probability.

On 66% of the trials, one of the distractors appeared in a unique color (red or green) but in the same shape as the other items (i.e., the distractor singleton). The rest of the trials were the no-distractor trials. The items in the search display appeared in one of six locations (0°, 60°, 120°, 180°, 240°, and 300° in polar angle) around an imaginary circle with a radius of 5.01°, and the singleton distractor could appear in one of these six locations as well. Yet, unbeknownst to the participants, two of these locations (randomly determined for each participant) had a high proportion, 32.56% of distractor-present trials each, to contain the distractor singleton (high-probability, or HP, location), with the other locations having a low proportion of 34.88% to contain the distractor singleton (low-probability, or LP, location).

Importantly, each HP location was paired with a *different* scene category, which provided the contextual information. For example, for a certain participant, on trials in which the background scene was a city scene, the HP location might have been in the 240° location in the display (see Figure 1), while on trials in which the background scene was a forest scene, the HP location might have been in the 60° location. Because the probability manipulation of the spatial location of the singleton distractor was contingent upon the background scene of the current trial, this created two critical display locations: (1) high-probability location for the current context (HP-current), indicating the location that had a higher probability of containing a singleton distractor with the current category scene in the background. Referring to the example above, these will be all the trials in which the scenes in the background were city scenes and the singleton distractor appeared at the 240° location, along with all the trials in which there were forest scenes in the background and the singleton distractor appeared at the 60° location (see Figure 1A left and right panels, respectively). (2) The second critical display location were trails in which the color singleton appeared at the high-probability location for the other context (HP-other), indicating the location that for the current trial has a low-probability to contain the singleton distractor, but serves as the HP location on trials in which the other category scene was in the background. In the example above, those will be all the trials with forest scenes in the background and in which the singleton distractor appeared at the 240°

location, along with all the trials with city scenes in the background in which the singleton distractor appeared at the 60º location (see Figure 1B right and left panels, respectively). About 6.7% of the distractor-present trials were HP-other trials, and about 66.7% of distractor-present trials were HP-current trials. Participants performed 9 blocks with 120 trials each, with all the conditions (HP-current, HP-other, LP, and no-distractor) randomly intermixed. There were about 480, 48, 192, and 360 trials in each of the HP-current, HP-other, LP, and no-distractor conditions (respectively), with about half of these trials embedded on top of city scenes and the other half embedded on top of forest scenes. Participants were given 10 practice trials and were asked to respond as quickly as possible.

Awareness Assessment. After the visual search task participants were presented with a black screen containing numbers in the possible locations of the items in the visual search task. Participants were asked to indicate via keypress which location they thought the odd color shape appeared most of the times when pictures in the background were of city scenes, and which location they thought the odd color shape appeared most of the times when pictures in the background were of forest scenes. In addition, participants were asked to rate their degree of confidence for the two responses on a scale between 1 (very unconfident) to 7 (very confident).

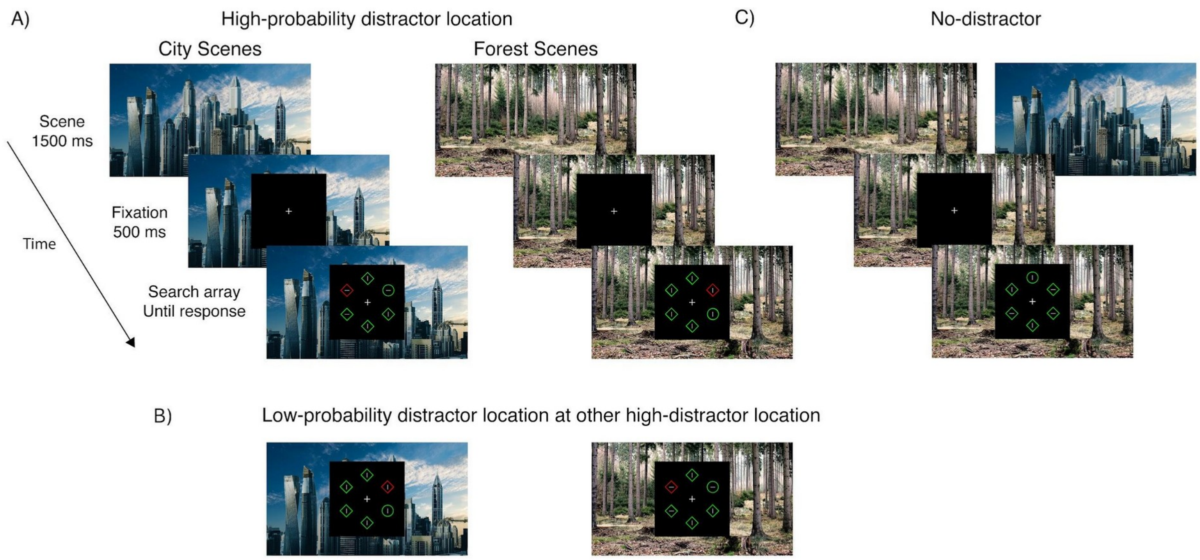

Figure 1. Trial sequence in Experiment 1. Participants were instructed to search for the odd shape and indicate the orientation of the line segment within the odd shape. (A) An example of a high-probability distractor location (HP–current) for city scenes (left) and forest scenes (right). (B) Example of a high-probability distractor location for the other context (HP-other) when the low-probability distractor is at the location of the high-probability distractor for the forest scenes (left) and city scenes (right). (C) Example of a no-distractor trial.

Results

Visual search task. Repeated measures analysis of variance (ANOVA) with category scene (city, forest) × distractor-probability (high-probability, low-probability, no-distractor) on mean RT as a dependent variable showed a main effect of distractor-probability ($F(2, 44) = 105.40$, $MSE = 3058.49$, $p < 0.0001$, $\eta_p^2 = 0.82$; See Figure 2). Planned comparisons corrected to FDR p-value of 0.05 (Benjamini & Hochberg, 1995) showed that RT in the HP condition was lower than RT in the LP condition ($t(44) = 4.34$, $p < 0.001$, $d = 0.23$), and that RT in the no-distractor condition was lower than RT in the HP condition ($t(44) = 9.82$, $p < 0.001$, $d = 0.52$). This pattern replicates previous findings suggesting that spatial regularities about task-irrelevant information can bias spatial attention away from locations with high-probability to contain task-irrelevant items (Wang & Theeuwes, 2018a, 2018b, 2018c). The main effect of category scene and the distractor-probability × category scene interaction was not significant ($F(1, 22) = 1.44$, $MSE = 1316.61$, $p = 0.24$; $F < 1$ for the category scene main effect and the category scene × distractor-probability interaction, respectively).

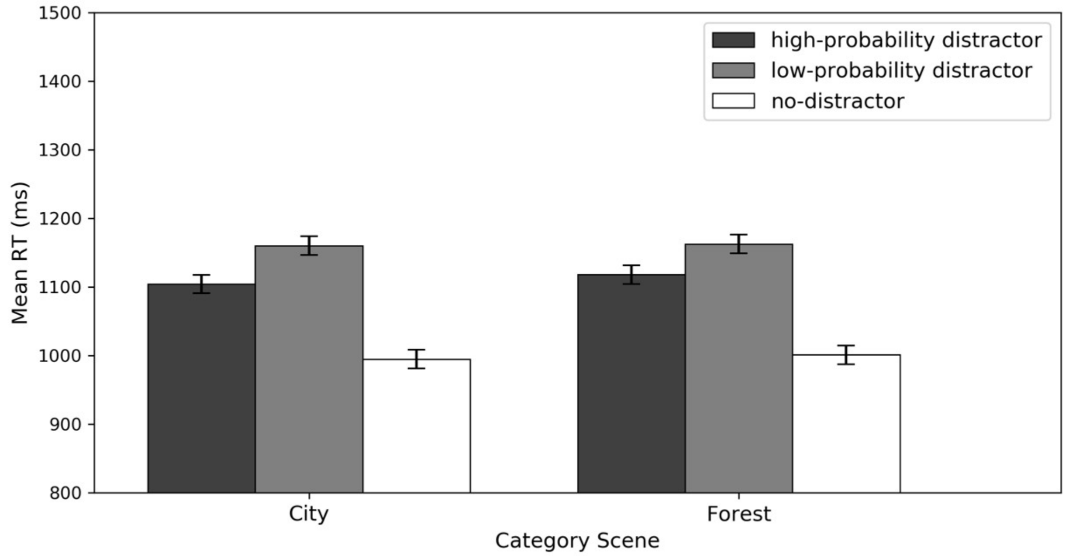

Figure 2. Results from Experiment 1. Mean reaction time as a function of category scene and distractor-probability. Error bars represent 95% confidence intervals according to Loftus & Masson (1994).

Repeated measures ANOVA category scene (city, forest) × distractor-probability (high-probability, low-probability, no-distractor) on mean accuracy as a dependent variable showed a main effect of distractor-probability ($F(2, 44) = 16.67$, MSE = 0.00, $p < 0.001$, $\eta_p^2 = 0.43$; See Table 1). Planned comparisons corrected to FDR p-value of 0.05 (Benjamini & Hochberg, 1995) showed that accuracy in the HP condition ($M = 0.94$, $SD = 0.05$) was similar to accuracy in the LP condition ($M = 0.93$, $SD = 0.05$; $t(44) = 1.54$, $p = 0.13$, $d = 0.15$), and that accuracy in the no-distractor condition ($M = 0.96$, $SD = 0.03$) was higher than accuracy in the LP condition ($t(44) = -5.59$, $p < 0.001$, $d = -0.56$), suggesting no speed-accuracy tradeoff. The main effect of category scene ($M = 0.94$, $SD = 0.04$;

$M = 0.94$, $SD = 0.05$; for city scene and forest scene across distractor-probability, respectively) and the category scene × distractor-probability interaction ($M = 0.94$, $SD = 0.05$; $M = 0.93$, $SD = 0.05$; $M = 0.96$, $SD = 0.03$; $M = 0.93$, $SD = 0.05$; $M = 0.93$, $SD = 0.05$; $M = 0.96$, $SD = 0.03$) was not significant ($F < 1$; $F < 1$ for the category scene main effect and the distractor-probability × category scene interaction, respectively).

To examine how the effect of distractor probability changed over time, repeated measures ANOVA with epoch (1, 2, 3; each epoch was three consecutive blocks in the experiment) × distractor-probability (high-probability current, high-probability other, low-probability) on mean RT as a dependent variable showed a main effect of distractor-probability ($F(2, 44) = 9.18$, MSE = 7002.66, $p < 0.001$, $\eta_p^2 = 0.29$) and epoch ($F(2, 44) = 34.44$, MSE = 28189.32, $p < 0.001$, $\eta_p^2 = 0.61$; See Figure 3). The distractor-probability × epoch interaction was not significant ($F < 1$). However, planned comparison showed that in epoch 3, RT in the HP-current condition was lower than RT in the HP-other condition ($t(22) = 2.17$, $p = 0.04$, $d = 0.14$), suggesting that context-dependent distractor suppression emerged in the third epoch.

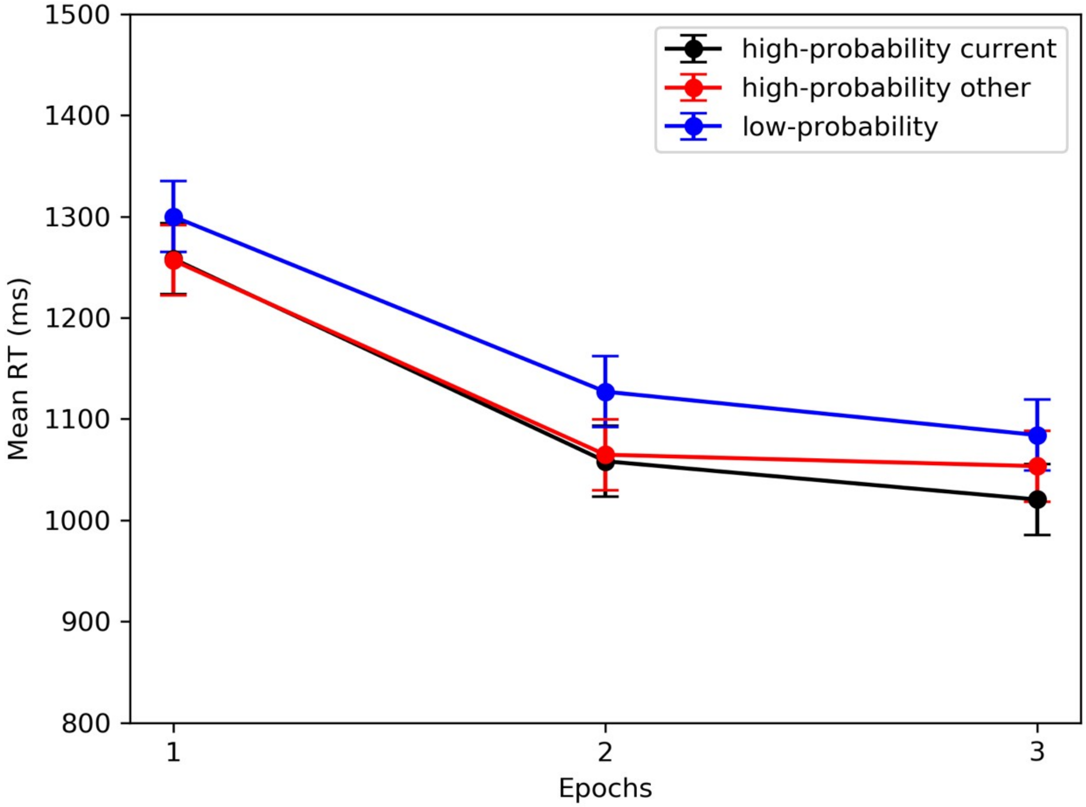

Figure 3. Results from Experiment 1. Mean reaction time as a function of distractor-probability and epoch. Error bars represent 95% confidence intervals according to Loftus & Masson (1994).

Repeated measures ANOVA with epoch (1, 2, 3) × distractor-probability (high-probability current, high-probability other, low-probability); on mean accuracy as a dependent variable showed that neither the main effect of distractor-probability ($M = 0.94$, $SD =0.05$; $M = 0.94$, $SD = 0.07$; $M = 0.93$, $SD = 0.05$) or epoch ($M = 0.93$, $SD = 0.07$; $M = 0.94$; $SD = 0.06$; $M = 0.93$, $SD = 0.05$), nor the epoch × distractor-probability interaction (*M* = 0.93, *SD* = 0.05; *M* = 0.92, *SD* = 0.10; *M* = 0.93, *SD* = 0.05; *M* = 0.94, *SD* = 0.06; *M* = 0.95, *SD* = 0.05; *M* = 0.92, *SD* = 0.06; *M* = 0.94, *SD* = 0.04; *M* = 0.94, *SD* = 0.07; *M* = 0.93, *SD* = 0.05), where significant. For the distractor-probability main effect and the distractor-probability × epoch interaction Mauchly's test showed a violation of the sphericity assumption, so we applied the Greenhouse-Geisser correction ($F(2, 44) = 1.41$, MSE = 0.00, $p = 0.25$, $\eta_p^2 = 0.06$; $F(1.49, 32.84) = 1.55$, MSE = 0.00, $p = 0.22$, $\eta_p^2 = 0.06$; $F(2.82, 62.14) = 2.09$, MSE = 0.00, $p = 0.08$, $\eta_p^2 = 0.08$ for the main effect of distractor-probability, epoch, and distractor-probability × epoch interaction, respectively). Planned comparison showed that in epoch 3, accuracy in the HP-current condition (*M* = 0.94, *SD* = 0.04) was similar to accuracy in the HP-other condition (*M* = 0.94, *SD* = 0.07; $t(22) = -0.17$, $p = 0.86$, $d = -0.03$), suggesting no speed-accuracy tradeoff.

Experiment 2

The results of Experiment 1 did not show clear support for context-dependent suppression. However, the results did appear to be consistent with a learning effect that emerged in the 3rd epoch. Here, we repeat Experiment 1 with a larger sample size, guided by power analysis, and we test the *a priori* prediction that a context-dependent effect emerges in the third epoch. This design, sample size, and analysis plan was pre-registered at the Open Science Foundation (https://osf.io/c5ur9/). The raw data files of participants included in the analysis were uploaded to the Open Science Foundation platform (https://osf.io/qys95/).

Method

Participants. Seventy-one students from The Ohio State University (43 women, 28 men, *M* = 20.71 years, *SD* = 6.04) participated in a 90 minutes experimental session in exchange for course credit. Twenty participants were excluded from the analysis due to either not finishing the experiment (15 participants), having error rates in the HP or LP that were more than 2.5 *SD* of the group (3 participants), or having more than 15% of trials removed in one of the High-probability (HP), Low-probability (LP), or no-distractor conditions because Reaction Times (RTs) were less than 100 ms or more than 3 *SD* above the participant's mean (2 participants). Therefore, data reported in the Results section was analyzed from the remaining 51 participants.

Sample size was based on a power analysis conducted on the data analyzed in Experiment 1. Power analysis (given power of 0.90 and alpha of 0.05, two-tailed paired t-test comparing the HP-current distractor location vs. the HP-other in the third epoch) revealed 51 subjects needed for testing this comparison.

Stimuli and Procedure. ***Visual Search Task.*** Participants performed the same task as in Experiment 1. However, in the current experiment each block had 150 trials, resulting in a total of 1350 trials.

Awareness Assessment. At the end of the visual search task participants were presented an assessment as in Experiment 1.

Results

Visual search task. Repeated measures ANOVA with distractor-probability (high-probability, low-probability, no-distractor) × category scene (city, forest) on mean RT as a dependent variable showed a main effect of distractor-probability. For this effect Mauchly's test showed a violation of the sphericity assumption, so we applied the Greenhouse-Geisser correction; the main effect was significant ($F(1.55, 77.59) = 123.17$, MSE = 6612.64, $p < 0.001$, $\eta_p^2 = 0.71$; See Figure 4). Planned comparisons corrected to FDR p-value of 0.05 (Benjamini & Hochberg, 1995) showed that RT in the HP condition was lower than RT in the LP condition ($t(50) = 6.77$, $p < 0.001$, $d = 0.14$), and that RT in the no-distractor condition was lower than RT in the HP condition ($t(50) = 10.09$, $p < 0.001$, $d = 0.33$). This pattern replicates the results of Experiment 1 and previous findings suggesting that spatial regularities about task-irrelevant information can bias spatial attention away from locations with high-probability to contain task-irrelevant items (Wang & Theeuwes, 2018a, 2018b, 2018c). The main effect of category scene and the distractor-probability × category scene interaction was not significant (Fs < 1 for both the category scene main effect and the distractor-probability × category scene interaction).

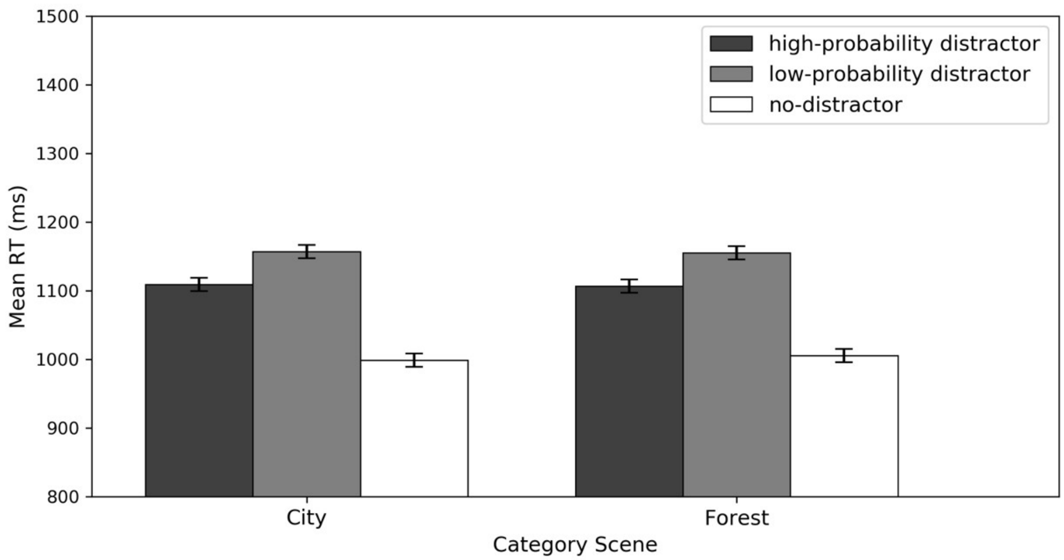

Figure 4. Results from Experiment 2. Mean reaction time as a function of category scene and distractor-probability. Error bars represent 95% confidence intervals according to (Loftus & Masson, 1994).

Repeated measures ANOVA category scene (city, forest) × distractor-probability (high-probability, low-probability, no-distractor) on mean accuracy as a dependent variable showed a main effect for distractor-probability. The category scene × distractor-probability interaction was marginally significant. For the distractor-probability main effect and the category scene × distractor-probability interaction Mauchly's test showed a violation of the sphericity assumption, so we applied the Greenhouse-Geisser correction ($F(1.53, 76.58) = 37.11$, MSE = 0.00, $p < 0.001$, $\eta_p^2 = 0.42$; $F(1.62, 81.19) = 3.00$, MSE = 0.00, $p = 0.065$, $\eta_p^2 = 0.05$; for the distractor-probability main effect and the category scene × distractor-probability interaction, respectively). The main effect for the category scene was not significant ($F < 1$). Planned comparisons corrected to FDR p-value of 0.05 (Benjamini & Hochberg, 1995) showed that accuracy in the HP condition ($M = 0.93$, $SD = 0.05$) was higher than accuracy in the LP condition ($M = 0.92$, $SD = 0.06$; $t(50) = 4.04$, $p < 0.001$, $d = 0.56$), and that accuracy in the no-distractor condition ($M = 0.95$, $SD = 0.04$) was higher than accuracy in the LP condition ($t(50) = 7.03$, $p < 0.001$, $d = 0.98$), suggesting no speed-accuracy tradeoff.

Repeated measures ANOVA with distractor-probability (high-probability current, high-probability other, low-probability) × epoch (1, 2, 3) on mean RT as a dependent variable showed a main effect of distractor-probability and epoch ($F(2, 102) = 34.24$, MSE = 1583029.688, $p < 0.001$, $\eta_p^2 = 0.40$; See Figure 5). For the distractor-probability main effect Mauchly’s test showed a violation of the sphericity assumption, so we applied the Greenhouse-Geisser correction; the main effect was significant ($F(1.55, 79.43) = 9.18$, MSE = 312060.05, $p < 0.001$, $\eta_p^2 = 0.35$). The distractor-probability × epoch interaction was not significant ($F < 1$). For our critical planned comparison, unlike in Experiment 1, there was no difference in Epoch 3 between the HP-current and HP-other conditions.

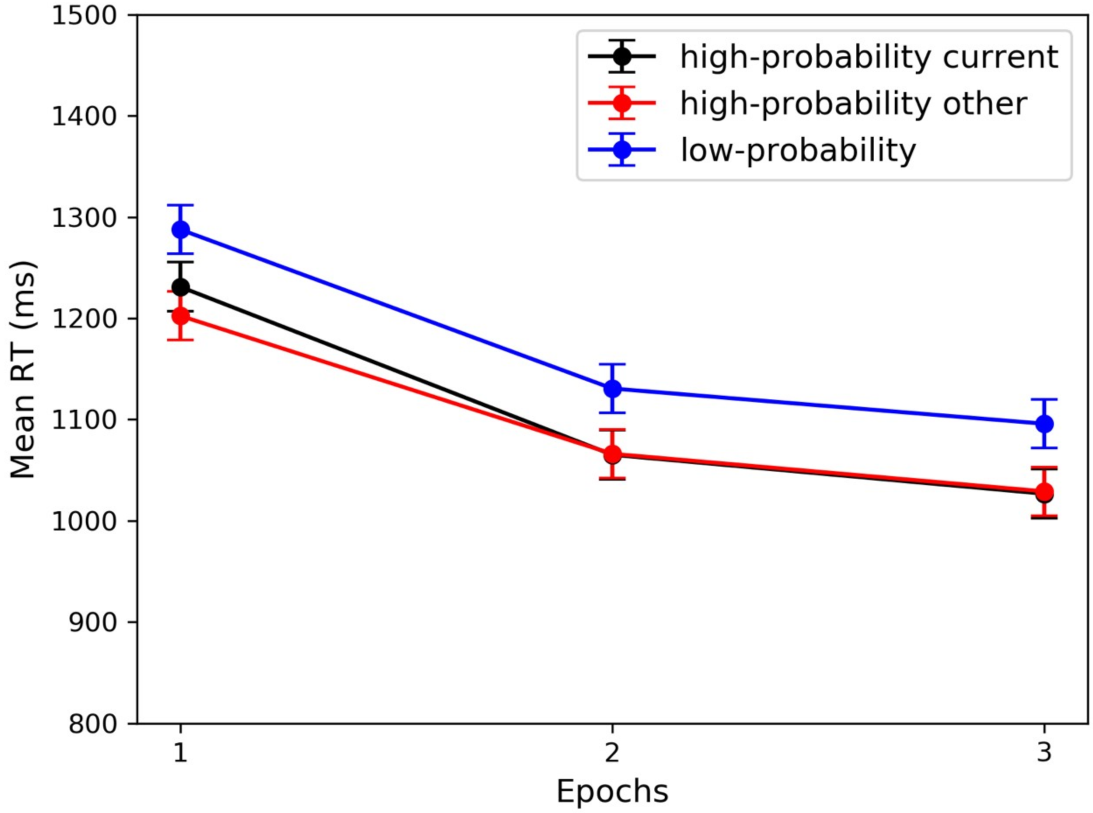

Figure 5. Results from Experiment 2. Mean reaction time as a function of distractor-probability and epoch. Error bars represent 95% confidence intervals according to Loftus & Masson (1994).

Repeated measures ANOVA with epoch (1, 2, 3) × distractor-probability (high-probability current, high-probability other, low-probability); on mean accuracy as a dependent variable showed a main effect of distractor-probability (M = 0.93, SD = 0.05; M = 0.93, SD = 0.08; M = 0.92, SD = 0.07). The distractor-probability main effect Mauchly's test showed a violation of the sphericity assumption, so we applied the Greenhouse-Geisser correction (F(1.64, 82.36) = 7.25, MSE = 0.00, p = 0.002, η_p^2 = 0.12). Neither the main effect for epoch (M = 0.93, SD = 0.06; M = 0.92; SD = 0.07; M = 0.93, SD = 0.07), nor the epoch × distractor-probability interaction (M = 0.94, SD = 0.04 ; M = 0.93, SD = 0.06; M = 0.93, SD = 0.06; M = 0.93, SD = 0.05; M = 0.93, SD = 0.09; M = 0.91, SD = 0.08; M = 0.93, SD = 0.06; M = 0.94, SD = 0.07; M = 0.91, SD = 0.08), were significant (F <1; F < 1; for the epoch main effect and epoch × distractor-probability interaction, respectively). Planned comparison showed that in Epoch 3, accuracy in the HP-current condition (M = 0.93, SD = 0.06) was similar to accuracy in the HP-other condition (M = 0.94, SD = 0.07 ; t(50) = -0.93, p = 0.35), suggesting no speed-accuracy tradeoff.

Discussion

In Experiment 1, we found tentative evidence for context dependency emerging in the later portion of the experiment. However, in this higher-powered replication attempt, we failed to confirm this finding, suggesting that the result was merely a Type-I error. Moreover, this failure was further corroborated by another data set. We attempted a stronger manipulation, in which we removed the no-distractor condition and included more trials – all other task aspects were the same as Experiment 2. We collected 21 valid participants in this additional experiment out of a planned set of 51 before the COVID-19 pandemic forced us to halt in-person data collection. Rather than waiting for the shut-down to end before resuming data collection, we decided to use the existing data for exploratory purposes ansd proceeded to analyze it. As in Experiment 2, results showed no hint of RT advantage in the high-probability current vs. the high-probability other conditions. We report these results in the supplement for this article.

Clearly, the method we have used up to this point has provided no evidence that learned spatial suppression is context-dependent, a finding that Britton and Anderson (2020) concurrently arrived at using a very similar approach. The results suggest that either 1) context-dependent suppression does not occur, or 2) our context manipulation is not sufficiently strong. The next two experiments provide a more focused attempt to elicit context-dependent control.

Experiment 3

Our use of background scenes was inspired by ecological considerations. Any context-dependent effects in the real world may be driven by rich environmental cues. However, simply placing images of scenes in the background may not fully approximate the immersive experience of switching behavioral context in the real world. One must locomote to move from one stimulus environment in the real world to another; more broadly, while people may be unaware of contextual learning they experience, they are likely aware of which environment they are in. It has previously been shown that incidental learning effects depend on attention to the statistical regularities that mediate them (Y. Jiang & Chun, 2001; Turk-Browne et al., 2005). Thus, for the next two experiments, our approach was to create stimuli that require participants to attend to the context. We also incorporated redundancy in the separation of context, by creating two distinct sets of stimulus shapes and colors for each participant. For example, a participant might search through blue and yellow pentagons and squares in one context, while they search through red and green circles and diamonds in the other context. To ensure that participants attended to the distinct contexts, they were told that they had to perform a line orientation judgment when one scene category was presented, while they had to perform a gap location judgment (left vs. right) when the other scene category was presented. The same set of six spatial locations was used for both tasks, and we used the same HP-current and HP-other contingencies used in previous experiments. If these modifications were sufficient to induce context-dependent suppression, then significantly faster performance should emerge in the HP-current than HP-other condition. The sample size, experimental design, and analysis plan were preregistered on the Open Science Foundation (https://osf.io/uy9dz/). The raw data files of participants included in the analysis were uploaded to the Open Science Foundation platform (https://osf.io/qys95/).

Methods

Participants. Sixty-four students from The Ohio State University (37 men, 27 women, M = 19.50 years, SD = 2.00; the age of one participant was not recorded) participated in a 90 minutes experimental session in exchange for course credit. Fourteen participants were excluded from the analysis because they either did not complete the task (9 participants), having error rates in the HP or LP that were more than 2.5 SD of the group (0 participants), or because their RTs were less than 100 ms or more than 3 SD above the participant's mean (5 participants). Therefore, data reported in the Results section was analyzed from the remaining 50 participants. While we collected our planned sample, one participant's data was lost. We discovered this issue during the facility shutdown related to the COVID-19 pandemic, and we thus opted to carry out the analysis one participant shy of the planned sample.

Stimuli and Procedure. ***Visual Search Task.*** Participants performed the same task as in Experiment 3 except for the following changes. The search display was composed from two pairs of stimuli: circles-diamonds, and pentagons-squares, with each pair of stimuli associated with a different category scene in the background of the search display (counterbalanced between participants). In each trial participants needed to search for the odd-shaped item (target) and report the orientation of the bar or the location of the gap inside the target. The task at hand (i.e., report the orientation of the bar or the location of the gap inside the target) was determined by the category scene in the background (counterbalanced between participants), such that half of the participants were asked to report the orientation of the bar inside the target whenever there was a city scene in the background, and report the location of the gap inside the target whenever there was a forest scene in the background (and vice versa for the rest of the participants). For each participant, the colors of the stimuli in the search array (red and green or blue and yellow) for city scenes and forest scenes were randomly chosen such that for some participants the colors of the stimuli in the city scenes were red and green, and blue and yellow for forest scenes, whereas for other participants the colors of the stimuli were blue and yellow for city scenes, and red and green for forest scenes.

Awareness Assessment. At the end of the visual search task participants were presented with the same assessment as in previous Experiments.

Results

Visual search task. Repeated measures ANOVA with category scene (city, forest) × distractor-probability (high-probability, low-probability) on mean RT as a dependent variable showed a main effect of distractor-probability. ($F(1, 49) = 47.41$, MSE = 4078.22, $p < 0.001$, $\eta_p^2 = 0.49$; See Figure 6). The main effect of category scene and the distractor-probability × category scene interaction was not significant ($F < 1$ and $F(1, 49) = 1.34$, MSE = 2737.96, $p = 0.25$ for the category scene main effect and the distractor-probability × category scene interaction, respectively).

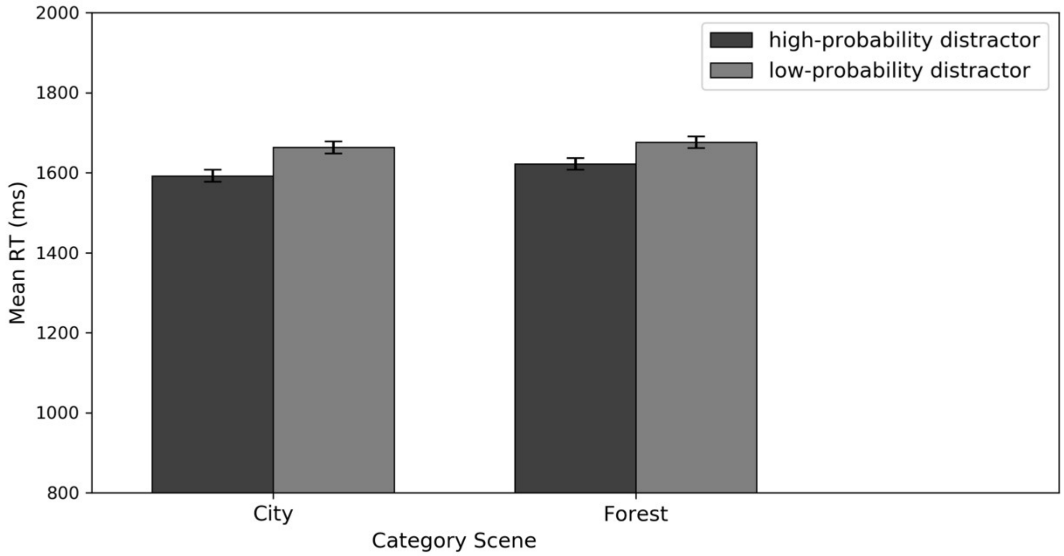

Figure 6. Results from Experiment 3. Mean reaction time as a function of category scene and distractor-probability. Error bars represent 95% confidence intervals according to Loftus & Masson (1994).

Repeated measures ANOVA category scene (city, forest) × distractor-probability (high-probability, low-probability) on mean accuracy as a dependent variable showed a main effect for distractor-probability (M = 0.939, SD = 0.03; M = 0.931, SD = 0.03; $F(1, 49) = 15.18$, MSE = 0.00, $p < 0.001$, $\eta_p^2 = 0.23$), suggesting no speed-accuracy tradeoff. The category scene main effect as well as the category scene × distractor-probability interaction were not significant ($F < 1$; $F < 1$; For the category scene main effect and the category scene × distractor-probability interaction, respectively).

Repeated measures ANOVA with epoch (1, 2, 3) × distractor-probability (high-probability current, high-probability other, low-probability) on mean RT as a dependent variable showed a main effect of distractor-probability and epoch. For both the main effects Mauchly's test showed a violation of the sphericity assumption, so we applied the Greenhouse-Geisser correction; results were significant ($F(1.64, 80.53) = 12.49$, MSE = 17831.77, $p < 0.01$, $\eta_p^2 = 0.20$ for distractor-probability and $F(1.75, 85.55) = 55.82$, MSE = 83761.91, $p < 0.01$, $\eta_p^2 = 0.53$ for epoch; See Figure 7). Post-hoc pairwise comparisons showed that across epochs, RT in the HP-current condition was significantly lower than RT in the HP-other condition ($t(49) = 3.54$, $p = 0.002$, $d = 0.10$), and in the LP condition ($t(49) = 4.82$, $p < 0.001$, $d = 0.14$), and that RT in the HP-other condition was similar to RT in the LP condition ($t(49) = 1.28$, $p = 0.606$). The epoch × distractor-probability interaction was not significant ($F(2.7, 132.32) = 1.51$, MSE = 19330.85, $\eta_p^2 = 0.03$; Greenhouse-Geisser correction due to violation of the sphericity assumption). Following Experiment 1, we carried out a planned comparison specifically in epoch 3 to compare the HP-current vs. HP-other conditions, although this difference was not significant ($t(49) = 0.93$, $p = 0.35$). Post-hoc comparisons did show that in epoch 1 and in epoch 2 RT in the HP-current condition was lower than in the HP-other condition ($t(49) = 2.16$, $p = 0.036$, $d = 0.30$; $t(49) = 2.53$, $p = 0.014$, $d = 0.35$, for epoch 1 and epoch 2, respectively).

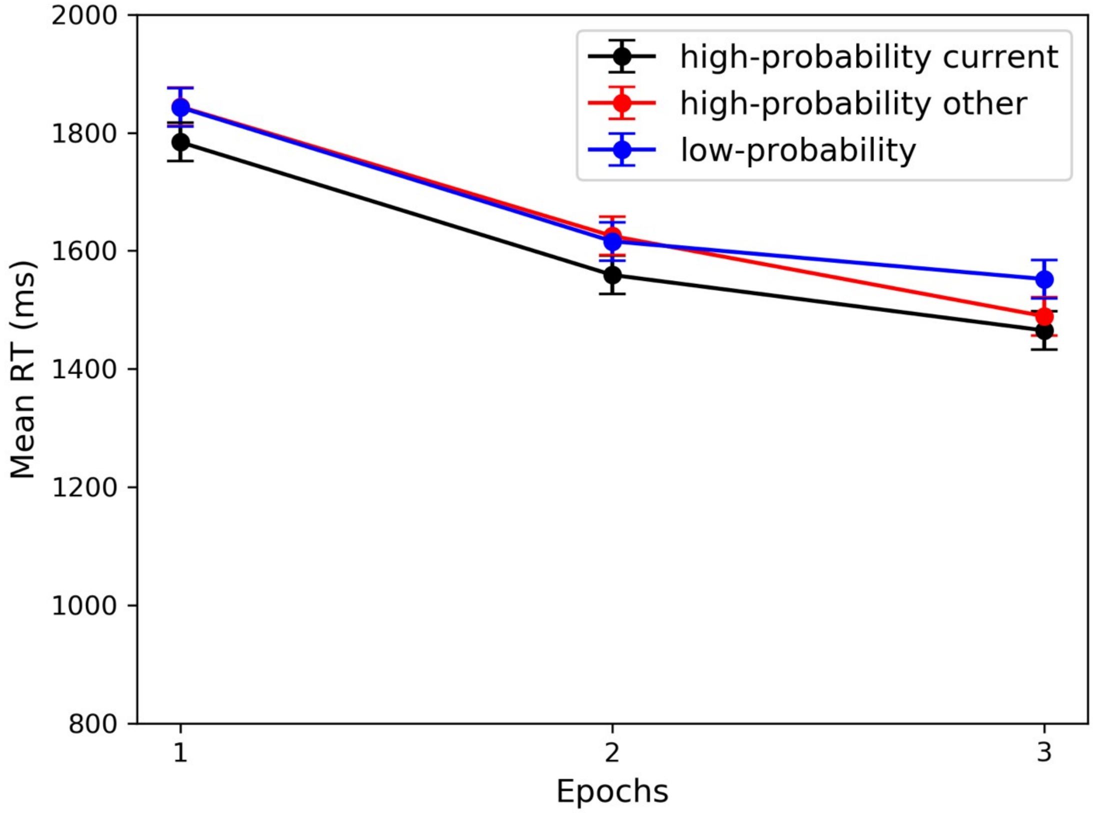

Figure 7. Results from Experiment 3. Mean reaction time as a function of distractor-probability and epoch. Error bars represent 95% confidence intervals according to Loftus & Masson (1994).

Repeated measures ANOVA with epoch (1, 2, 3) × distractor-probability (high-probability current, high-probability other, low-probability) on mean accuracy as a dependent variable showed a marginally significant main effect of distractor-probability (M = 0.93, SD = 0.03; M = 0.92, SD = 0.06; M = 0.92, SD = 0.04; (F(1.37, 67.41) = 3.23, MSE = 0.00, p = 0.063,

η_p^2 = 0.06; Greenhouse-Geisser corrected). Neither the main effect for epoch (*M* = 0.93, *SD* = 0.04; *M* = 0.93; *SD* = 0.04; *M* = 0.92, *SD* = 0.05), nor the epoch × distractor-probability interaction (*M* = 0.93, *SD* = 0.03; *M* = 0.93, *SD* = 0.06; *M* = 0.93, *SD* = 0.04; *M* = 0.94, *SD* = 0.03; *M* = 0.93, *SD* = 0.06; *M* = 0.93, *SD* = 0.04; *M* = 0.93, *SD* = 0.04; *M* = 0.92, *SD* = 0.06; *M* = 0.92, *SD* = 0.05), were significant ($F(1.86, 82.60) = 1.92$, MSE = 0.00, $p = 0.15$, η_p^2 = 0.03; Greenhouse-Geisser corrected; $F < 1$; for the epoch main effect and epoch × distractor-probability interaction, respectively). Planned comparison showed that in Epoch 3, accuracy in the HP-current condition (*M* = 0.93, *SD* = 0.04) was similar to accuracy in the HP-other condition (*M* = 0.92, *SD* = 0.06; $t(49) = 1.09$, $p = 0.27$), suggesting no speed-accuracy tradeoff.

Experiment 4

Upon reinforcing the distinction between the two contexts and requiring attention to them, we now observe evidence for context-dependent suppression; overall, HP-current RT was faster than HP-other RT. Given three previous failures to find clear context dependency (Experiments 1 and 2, and Supplementary Experiment A), along with other reported failures in the literature (Britton & Anderson, 2020; De Waard et al., 2022), we pursue in this experiment a pre-registered replication attempt of Experiment 3, with an identical design and procedure. The raw data files of participants included in the analysis were uploaded to the Open Science Foundation platform (https://osf.io/qys95/).

Methods

Participants. Seventy students from The Ohio State University (32 females, *M* = 20.65 years, *SD* = 5.40) participated in a 90-minute experimental session in exchange for course credit. Nineteen participants were excluded from the analysis because either they did not complete the task (11 participants), having error rates in the HP or LP that were more than 2.5 *SD* of the group (10 participants), or their RTs were less than 100 ms or more than 3 *SD* above the participant's mean (0 participants). Therefore, data reported in the Results section was analyzed from the remaining 49 participants. While planned for a data set of 51 valid participants, logistical issues relating to the COVID-19 pandemic led us to carry out analysis with the existing set of participants.

Stimuli and Procedure. Participants performed the visual search task and awareness assessment as in Experiment 3.

Results

Visual search task. Repeated measures ANOVA with distractor-probability (high-probability, low-probability) × category scene (city, forest) on mean RT as a dependent variable showed a main effect of distractor-probability ($F(1, 48) = 27.92$, MSE = 5312.300, $p < 0.001$, $\eta_p^2 = 0.36$; See Figure 8). The main effect of category scene and the distractor-probability × category scene interaction were not significant ($F < 1$; $F(1, 48) = 3.63$, MSE = 3213.31, $p = 0.06$ for the category scene main effect and the distractor-probability × category scene interaction, respectively).

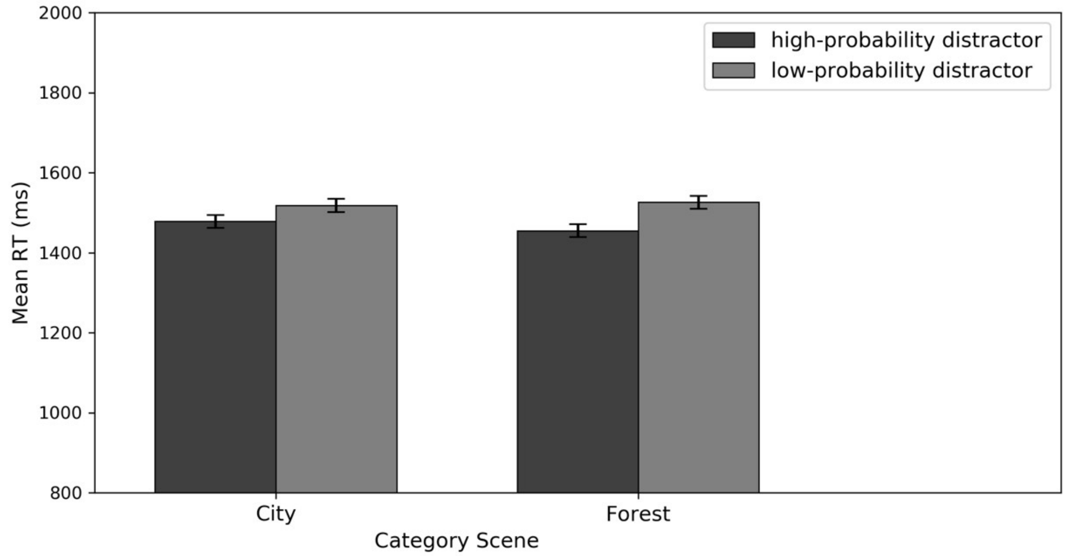

Figure 8. Results from Experiment 5. Mean reaction time as a function of category scene and distractor-probability. Error bars represent 95% confidence intervals according to Loftus & Masson (1994)

Repeated measures ANOVA category scene (city, forest) × distractor-probability (high-probability, low-probability) on mean accuracy as a dependent variable showed a main effect for distractor-probability (M = 0.91, SD = 0.04; M = 0.90, SD = 0.04; $F(1, 48) = 16.50$, MSE = 0.00, $p < 0.001$, $\eta_p^2 = 0.25$), suggesting no speed-accuracy tradeoff. The category scene (M = 0.90, SD = 0.04; M = 0.91, SD = 0.04) main effect as well as the category scene × distractor-probability interaction (M = 0.91, SD = 0.04; M = 0.90, SD = 0.04; M = 0.91, SD = 0.04; M = 0.90, SD = 0.04) were not significant ($F < 1$; $F < 1$; For the category scene main effect and the category scene × distractor-probability interaction, respectively).

Repeated measures ANOVA with distractor-probability (high-probability current, high-probability other, low-probability) × epoch (1, 2, 3) on mean RT as a dependent variable showed a main effect of distractor-probability and epoch. Mauchly's test showed a violation of the sphericity assumption for the distractor-probability effect, so we applied the Greenhouse-Geisser correction ($F(1.76, 84.53) = 11.33$ MSE = 15947.24, $p < 0.001$, $\eta_p^2 = 0.19$ for the distractor-probability; $F(2, 96) = 19.65$, MSE =97518.64, $p < 0.001$, $\eta_p^2 = 0.29$ for epoch; See Figure 9). Post-hoc pairwise comparisons showed that across epochs, RT in the HP-current condition was significantly lower than RT in the HP-other condition ($t(48) = 3.27$, $p = 0.004$, $d = 0.46$), and in the LP condition ($t(48) = 5.28$, $p < 0.001$, $d = 0.76$), and that RT in the HP-other condition was similar to RT in the LP condition ($t(48) = 1.38$, $p = 0.174$). The distractor-probability × epoch interaction was not significant ($F < 1$). Planned comparison showed that similar to Experiments 2-3 and replicating the results of Experiment 3, in epoch 3 the high-probability current condition was not lower than RT in the high-probability other condition ($t(48) = 1.79$, $p = 0.07$, $d = 0.25$). Post-hoc comparison showed that in epoch 1 the high-probability current condition was lower than RT in the high-probability other condition ($t(48) = 2.08$, $p = 0.04$, $d = 0.29$), but similar in epoch 2 ($t(48) = 1.90$, $p = 0.06$).

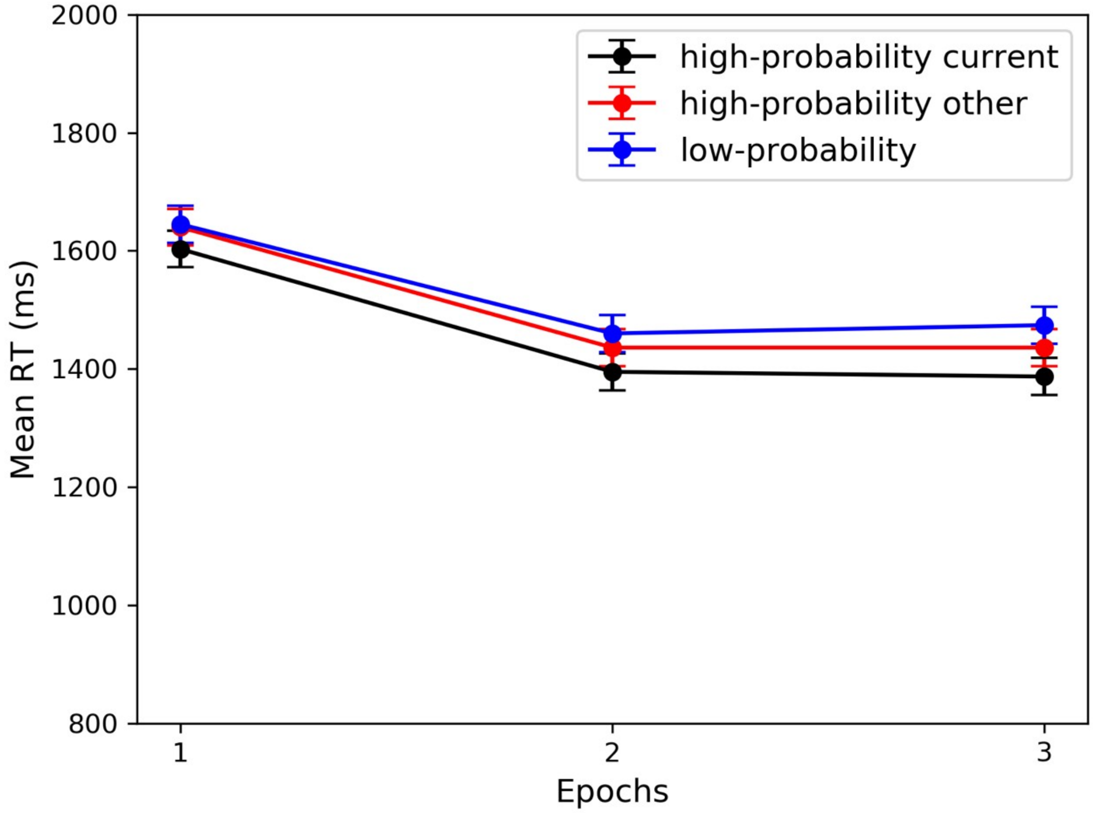

Figure 9. Results from Experiment 5. Mean reaction time as a function of distractor-probability and epoch. Error bars represent 95% confidence intervals according to Loftus & Masson (1994).

Repeated measures ANOVA with epoch (1, 2, 3) × distractor-probability (high-probability current, high-probability other, low-probability) on mean accuracy as a dependent variable showed a main effect of distractor-probability (M = 0.91, SD = 0.04; M = 0.91, SD = 0.07; M = 0.90, SD = 0.05; (F(1.47, 70.72) = 4.46, MSE = 0.00, p = 0.024, η_p^2 = 0.08; Greenhouse-Geisser corrected). Neither the main effect for epoch (M =

0.91, *SD* = 0.05; *M* = 0.90; *SD* = 0.05; *M* = 0.90, *SD* = 0.60), nor the epoch × distractor-probability interaction (*M* = 0.91, *SD* = 0.04; *M* = 0.91, *SD* = 0.07; *M* = 0.90, *SD* = 0.05; *M* = 0.91, *SD* = 0.04; *M* = 0.91, *SD* = 0.06; *M* = 0.89, *SD* = 0.05; *M* = 0.91, *SD* = 0.05; *M* = 0.90, *SD* = 0.08; *M* = 0.90, *SD* = 0.06), were significant ($F < 1$; $F < 1$; for the epoch main effect and epoch × distractor-probability interaction, respectively). Planned comparison showed that in Epoch 3, accuracy in the HP-current condition (*M* = 0.91, *SD* = 0.05) was similar to accuracy in the HP-other condition (*M* = 0.90, *SD* = 0.08; $t(48) = 0.55$, $p = 0.58$), suggesting no speed-accuracy tradeoff.

Awareness Assessment Analysis

We present the results of the awareness assessments for all experiments here. Since each participant only contributed two data points, we did not anticipate high statistical power for these analyses and did not include specific analyses in our preregistration plans. We opted to compute the 95% Highest Density Intervals (HDI) of the chance multinomial distribution by generating the random multinomial probabilities of each response outcome (i.e., correct guess for both locations, one location, or none of the locations). Since participants were allowed to guess the same location twice, there were 36 possible response outcomes: one of getting both guesses right, 10 of getting one guess right, and 25 of getting both guesses wrong. Then, across 10,000 random samples of these 36 possible outcomes array, we estimated multinomial probability ranges. Results showed that for getting both guesses right, proportion correct (i.e., mean correct guesses) was within the HDI in Experiments 1-2 and above the upper bound of the HDI in Experiments 3-4, and when collapsing across Experiments 3-4. As for getting one guess right, proportion correct was within the HDI in Experiments 1, 2, and 4, but above the upper bound in Experiment 3 and when collapsing across experiments (See Figure 10). Overall, these results suggest participants did not explicitly learn the regularities in Experiments 1 and 2, but at least some might have done so in Experiments 3-4.

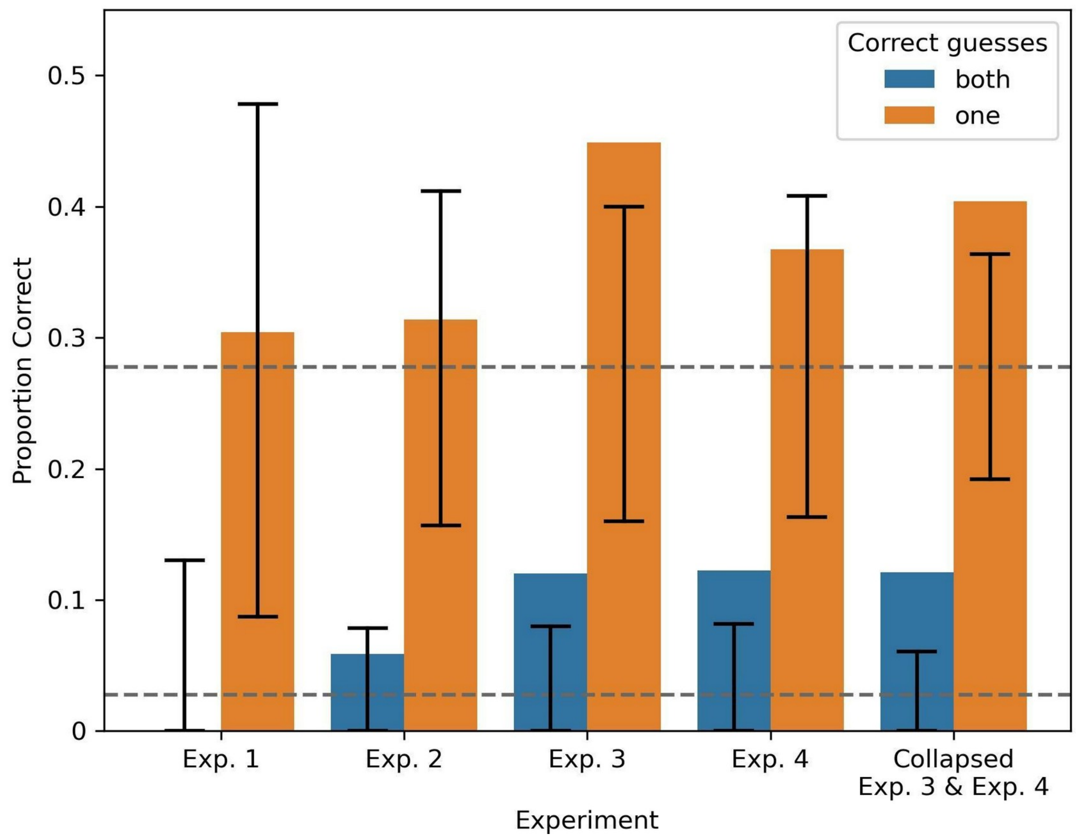

Figure 10. Proportion correct for guessing one and both locations of the high-probability distractor for each category scene in Experiments 1-4, and collapsed across Experiments 3-4. Error bars represent 95% HDI of chance multinomial distribution by generating the random multinomial probabilities of each response outcome across 10,000 random samples.

Note that participants might have been disinclined to choose the same option twice when guessing the locations of the odd color shape. Therefore, we also calculated another multinomial distribution constraining the number of options in which subjects choose among 6 items for the first choice and the remaining 5 items for the 2nd choice (see Supplementary Figure S3). Results showed that for getting both guesses right, proportion correct was within the HDI in Experiments 1-3, and above the upper bound of the HDI in Experiment 4, and when collapsing across Experiments 3-4. As for getting one guess right, proportion correct was within the HDI in Experiments 1, 2, , and Experiment 4, but above the upper bound in Experiment 3, and when collapsing across Experiments 3-4.

It is notable that we find evidence for above-chance awareness of the regularities for the two experiments that show robust context-dependent suppression. While performance in these two experiments was only modestly above chance levels, these results differ from the previous ones in that participants knew that the background scenes cued the relevant reported feature set (orientation or gap). It is sensible that this change made it more likely for participants to become explicitly aware of the pairing between scenes/stimuli and HP distractor locations. The results also prompt us to question whether explicit awareness is necessary for context-dependent suppression, as argued by De Waard et al. (2022). To address this question, we pooled data from Experiments 3 and 4 and included only participants who guessed the incorrect HP location for both city and forest backgrounds (N=47). Among this group, we compared the RTs for HP-current and HP-other across epochs and found that RT in the HP-current condition was significantly lower than RT in the HP-other condition ($t(46) = 3.96$, $p < 0.001$, $d = 0.12$), and in the LP condition ($t(46) = 7.03$, $p < 0.001$, $d = 0.18$), and that RT in the HP-other condition was similar to RT in the LP condition ($t(46) = 1.38$, $p = 0.174$) (see Figure 11). Thus, these results show that, for the present study, and in contrast to De Waard et al. (2022), explicit awareness does not appear to be necessary for context-dependent suppression.

Comparing accuracy for HP-current and HP-other across epochs within this group showed that accuracy in the HP-current condition ($M = 0.93$, $SD = 0.04$) was similar to accuracy in the HP-other condition ($M = 0.92$, $SD = 0.06$; ($t(46) = 1.32$, $p = 0.37$), and to accuracy in the LP condition ($M = 0.92$, $SD = 0.04$; $t(46) = 1.78$, $p = 0.23$), and that accuracy in the HP-other condition was similar to accuracy in the LP condition ($t(46) = 0.46$, $p = 0.64$), suggesting no speed-accuracy tradeoff.

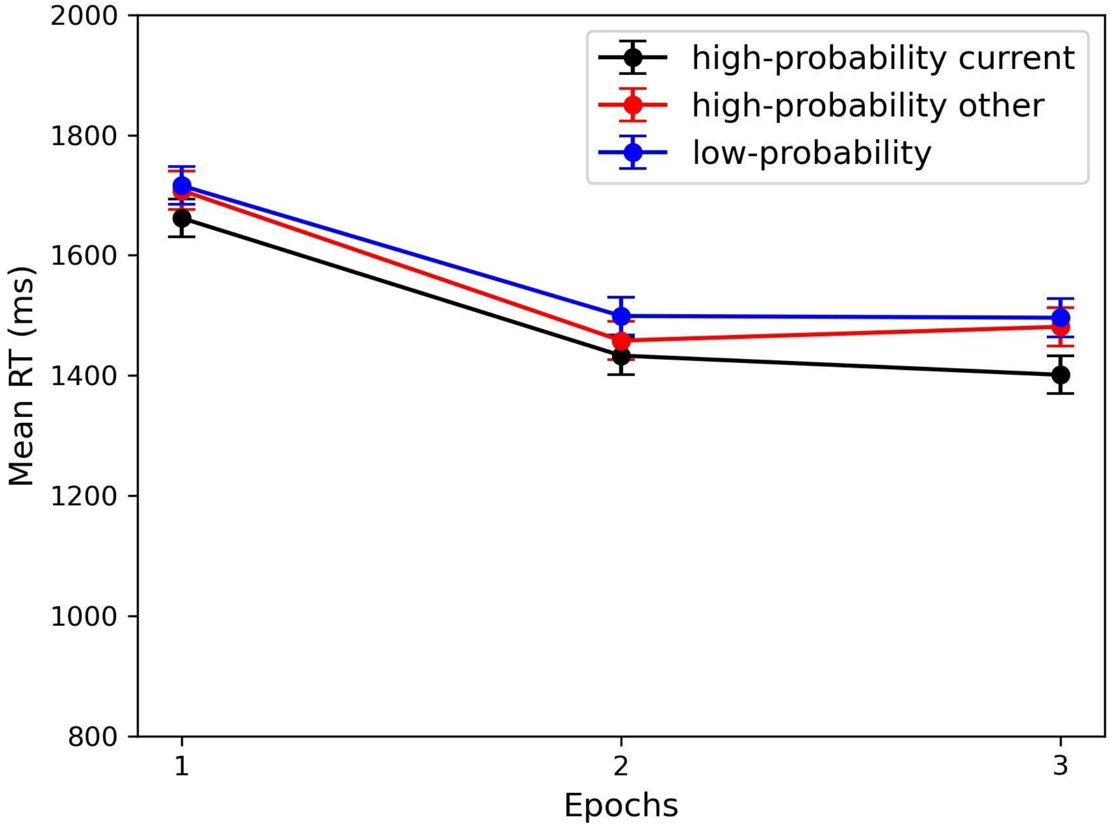

Figure 11. Results of the pooled data from Experiments 3 and 4 that included only participants who guessed the incorrect HP location for both city and forest backgrounds. Mean reaction time as a function of distractor-probability and epoch. Error bars represent 95% confidence intervals according to Loftus & Masson (1994).

General Discussion

In this study, we set out to investigate whether learned spatial suppression is context-invariant or context-dependent. The extant research prior to embarking on our study was conflicting. On the one hand, Leber et al. (2016) produced evidence that suppressed distractor locations could vary from trial to trial depending on implicitly-learned cues. However, that study relied on a complex relationship between explicitly cued target locations and implicitly learned distractor locations. Wang & Theeuwes (2018a) paradigm, which isolates a purer learned spatial suppression effect, several studies had failed to produce clear implicitly-learned context-dependent effects.

The failures to find context dependency, including those of Britton & Anderson,
(2020) and De Waard et al. (2022) may have been taken as evidence for context invariance in the Wang & Theeuwes (2018) paradigm. Our Experiments 1, 2, and our pilot experiment reported in the Supplement, taken together, appear consistent with these papers. These failures to find context-dependent effects in the laboratory could mean either a) they do not exist, or b) the manipulations were not strong enough. In Experiments 3 and 4, we strengthened the link between context and task, and we found significant context-dependent suppression effects.

Between the time we collected our data and submitted this work, two new studies have conceptually corroborated our findings.

Gao et al. (2023) associated one high-probability location with displays containing 4 items and another high-probability location with displays containing 10 items, and they found that the suppressed location could vary with these two display configurations. This result may seem surprising, since participants could not know the high-probability distractor location prior to the moment of search display onset, suggesting that suppression would need to be implemented extremely rapidly, or perhaps in a reactive fashion. We had designed our scene manipulation to give participants ample time (1500 ms) to update their suppressed location, but perhaps this was not necessary. It is possible, nevertheless, that the signature of suppression that we observed in our study may also not have been proactive in nature (see Chang et al., 2023).

De Waard et al. (2023) used a similar task-context pairing as us, linking a line orientation judgment to one high probability location and a detection task to another high probability location. However, whereas we used background scenes to cue the task type, they separated tasks by block, where participants performed Task A (with one HP distractor location) in the first block, Task B in the second block (with a different HP distractor location), and then a test block of Task A with equiprobable distractor locations. They found faster RTs on trials with context-congruent distraction locations during test, supporting context dependent suppression. These results are consistent with our findings, although they leave open the question of whether observers can flexibly update the to-be-suppressed location, depending on context, from trial to trial The present results demonstrate such momentary flexibility (see also Leber et al., 2016).

One key limitation of the present study relates to our efforts to obtain a strong manipulation. In addition to pairing background scenes to the high probability locations, we also paired the task (line vs. gap judgment) and properties of the search stimuli (shapes and colors) with the high-probability locations. Therefore, while we used identical spatial locations in both tasks, we cannot say for sure which aspects of the tasks were necessary to produce the context-dependent suppression. Future work can scale back the redundant aspects of our manipulation to address this question.

In conclusion, the present work provides key evidence for a flexible context-dependent mechanism of learned spatial suppression. Such results may be difficult to observe in the laboratory; however, we speculate that in the real world, which is likely replete with many redundant reinforcements of the relationship between context and behaviorally irrelevant locations, learned spatial suppression may indeed be highly context dependent.

Acknowledgments

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Declarations

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

Ethics Approval

All experiments and protocols were approved by the Behavioral and Social Sciences Institutional Review Board at The Ohio State University, and participants were treated in accordance with the ethical standards of the American Psychological Association and the Declaration of Helsinki.

Consent to Participate

Participants in all experiments gave their informed consent at the beginning of the experiment.

Consent for Publication

Participants in all experiments consented to the publication of their de-identified data.

Open Practices

The sample sizes, method, and analyses for Experiments 2 and 4 were pre-registered, with links provided in each respective experiment. Any deviations from the pre-registration plans are noted within each experiment.

Availability of Data and Materials

Data from all experiments are publicly available, with links provided in the method section of each experiment.

Code Availability

Experiment code will be shared upon request.

Authors' Contributions

A.S.A. and A.B.L. jointly generated the experiment ideas, designed the experiments, developed the analysis plan, and wrote the manuscript. A.S.A. coded the experiments and analyzed the data.

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Supplementary Experiment A

The raw data files of participants included in the analysis were uploaded to the Open Science Foundation platform (https://osf.io/qys95/).

Methods

Participants. Twenty-one students from The Ohio State University (10 women, 11 men, $M = 20.73$ years, $SD = 3.17$. Age of two participants were not recorded) participated in a 90-minute experimental session in exchange for course credit. One participant was excluded from the analysis due to either not finishing the experiment (0 participants), having error rates in the HP or LP that were more than 2.5 SD of the group (0 participants) RTs were less than 100 ms or more than 3 SD above the participant's mean (1 participant). Therefore, data reported in the Results section was analyzed from the remaining 20 participants. We planned to collect data from a total of 51 valid participants. However, due to a shutdown in data collection during the COVID-19 pandemic, we halted data collection for a prolonged period of time.

Stimuli and Procedure. ***Visual Search Task.*** Participants performed the same task as in Experiment 2 except for the following changes. In the current experiment we omitted the no-distractor condition. Furthermore, on each trial the probability for the HP-current distractor location was 75%, and the probability for the LP distractor location condition was 25%. Out of the LP trials, the probability for a HP-other trial was 1/5. Each block had 150 trials, resulting in a total of 1350 trials.

Survey. At the end of the visual search task participants were presented a survey as in Experiment 1 except that at the beginning of the survey they were asked to indicate via Yes/No key press if they notice the odd color item appeared in a certain location more when the background scenes were city scenes, and in another location more when the background scenes were forest scenes.

Results

Visual search task. Repeated measures ANOVA with distractor-probability (high-probability, low-probability) × category scene (city, forest) on mean RT as a dependent variable showed a main effect of distractor-probability. ($F(1, 19) = 10.47$, MSE = 4423.50, $p < 0.01$, $\eta_p^2 = 0.35$; See Figure S1). The main effect of category scene and the distractor-probability × category scene interaction was not significant (Fs < 1 for both the category scene main effect and the distractor-probability × category scene interaction).

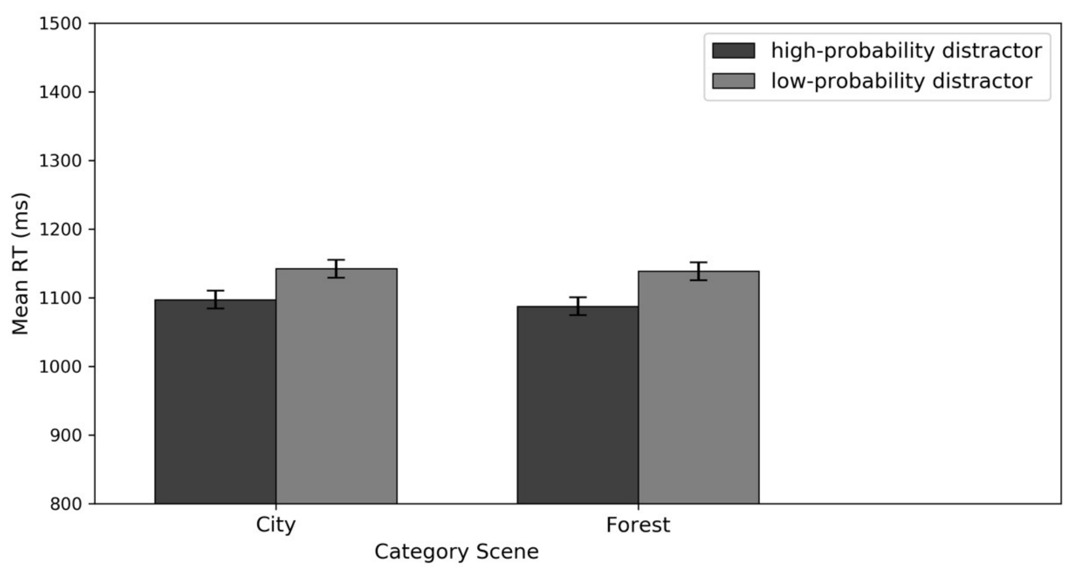

Figure S1. Results from Experiment 3. Mean reaction time as a function of category scene and distractor-probability. Error bars represent 95% confidence intervals according to (Loftus & Masson, 1994).

Repeated measures ANOVA with distractor-probability (high-probability current, high-probability other, low-probability) × epoch (1, 2, 3) on mean RT as a dependent variable showed a main effect of distractor-probability ($F(1, 38) = 13.63$, MSE = 11011.83, $p < 0.001$, $\eta_p^2 = 0.41$) and epoch ($F(2, 38) = 18.29$, MSE = 30531.55, $p < 0.001$, $\eta_p^2 = 0.49$; See Figure S2). The distractor-probability × epoch interaction was not significant ($F < 1$). Planned comparison showed that similar to Experiment 2 and unlike Experiment 1, in epoch 3 the high-probability current condition was not lower than RT in the high-probability other condition ($t(19) = 2.27$, $p = 0.21$). Post-hoc comparison showed that in epoch 1 RT in the high-probability current condition was not lower than RT in the high-probability other condition ($t(19) = 1.25$, $p = 0.22$).

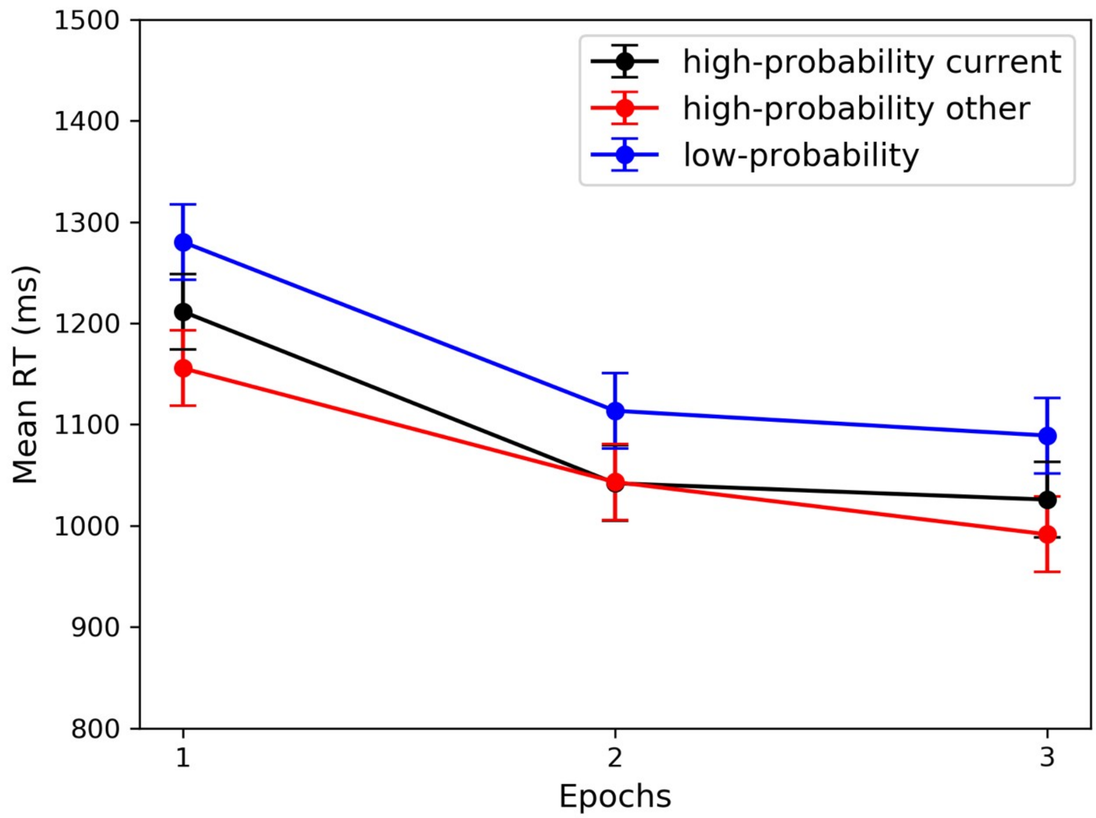

Figure S2. Results from Experiment 3. Mean reaction time as a function of distractor-probability and epoch. Error bars represent 95% confidence intervals according to (Loftus & Masson, 1994).

Supplementary Figures

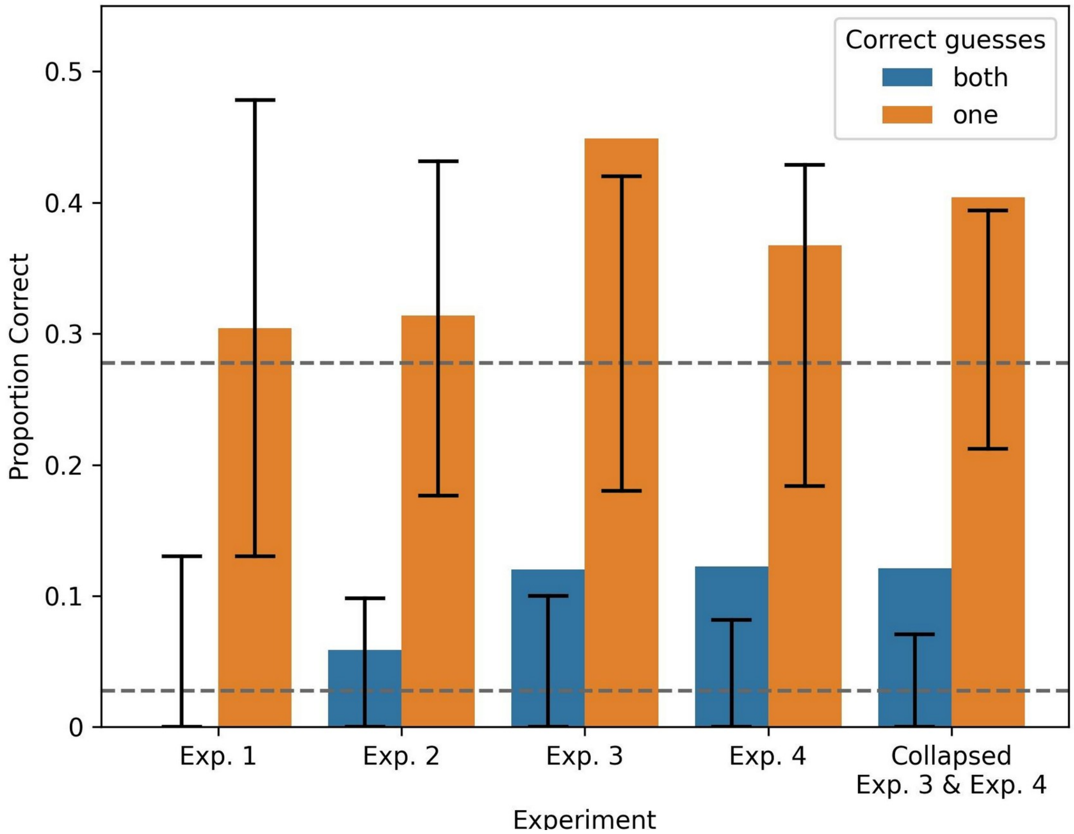

Figure S3. Proportion correct for guessing one and both locations of the high-probability distractor for each category scene in Experiments 1-4, 5 and collapsed across Experiments 3-4. Error bars represent 95% HDI of chance multinomial distribution by generating the random multinomial probabilities of each response outcome across 10,000 random samples with the constraint of not choosing the same location twice.