AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: Human Perception and Performance

ISSN: 0096-1523

2021, Vol. 47, No. 8, 1056–1062
https://doi.org/10.1037/xhp0000925

OBSERVATION

Attentional Suppression in Time and Space

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Distraction by a salient object can be reduced when we implicitly learn to suppress its most likely location. The current study investigated whether this suppression can also be tuned to the time at which the distractor is likely to appear. Participants performed the additional singleton task, in which they searched for a unique shape while a color singleton distractor was present. Following the fixation point, the search display was presented either after a short (500 ms) or long (1,500 ms) time interval. Critically, the color singleton distractor was presented relatively frequently at one high probability location after the short interval and at another high probability location after the long interval. The results showed that attentional capture at the two high probability locations was reduced relative to low probability distractor locations. More importantly, this reduction was greater when the color singleton distractor appeared at a high probability location after its associated interval than after the other interval. These findings indicate that participants learn to suppress particular locations at particular moments in time, suggesting that the spatial priority map of attentional selection is dynamically adjusted during the trial.

Public Significance Statement
It is important that we are able to suppress irrelevant salient objects to prevent interference in our daily activities. This study shows that we are able to learn not only where to suppress irrelevant objects but also when to suppress them.

Keywords: attention, attentional capture, spatial attention, statistical learning, temporal attention

Supplemental materials: https://doi.org/10.1037/xhp0000925.supp

Our environment contains a great deal of information, which poses challenges to attentional selection. Fortunately, there are many regularities embedded in this dynamic visual world, which makes the environment predictable. Studies of statistical learning (SL) have revealed that individuals are sensitive to regularities occurring in space and time even though there is little, if any, awareness of these regularities (Fiser & Aslin, 2001; Saffran et al., 1996). In turn, the extraction of these regularities biases visual attention in an automatic and implicit way (Turk-Browne et al., 2005; Zhao et al., 2013).

It has been argued that the lingering biases attributable to visual statistical learning (VSL) of spatial regularities play an important role in attentional selection (Awh et al., 2012; Failing & Theeuwes, 2018; Theeuwes, 2018, 2019). For instance, it was shown that search efficiency was enhanced for targets presented at probable locations relative to less probable locations even though participants were unaware of these regularities (Geng & Behrmann, 2002, 2005; Jiang et al., 2013).

VSL of distractor locations also bias attentional selection (Ferrante et al., 2018; Goschy et al., 2014). Recently, Wang and Theeuwes (2018a, 2018b, 2018c) demonstrated VSL of distractor locations using the additional singleton paradigm (Theeuwes, 1991, 1992), in which the distractor singleton appeared much more often at one (high probability) location than at any of the other (low probability) locations. When a distractor singleton appeared at the high probability location, it interfered less with target selection than when it appeared at a low probability location. It was concluded that the high probability distractor location was suppressed relative to all other locations (Wang et al., 2019). Overall, implicit spatial regularities bias attention toward locations that are likely to contain a target and away from locations that are likely to contain a distractor (Ferrante et al., 2018; Wang & Theeuwes, 2018b).

In addition to spatial regularities, temporal regularities can also bias attention (Nobre & van Ede, 2018; Olson & Chun, 2001). For

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Jan Theeuwes was supported by a European Research Council (ERC) advanced Grant 833029 – [LEARNATTEND]. Zhenzhen Xu was supported by a CSC scholarship (201906990033).

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instance, the duration and variability of the interval between the offset of a neutral waring signal and the onset of a target can bias attention implicitly (Los et al., 2017, 2021; Niemi & Näätänen, 1981; Rolke, 2008). Extending this basic paradigm, Wagener and Hoffmann (2010) varied the interval in combination with the location of the target (or its identity). In particular, they presented the target much more frequently at one location after a short interval and at another location after a long interval. The results showed that participants performed better when the target was presented at the location predicted by the interval than at the location not predicted by the interval. This implicit behavioral adaptation to spatiotemporal regularities of target has also been confirmed in several other studies (Pfeuffer et al., 2020; Rieth & Huber, 2013; Thomaschke & Dreisbach, 2015; Thomaschke et al., 2015).

Some research showed the possibility that implicit temporal regularities can also modulate distractor interference. Wendt and Kiesel (2011) associated different intervals with low and high proportions of conflict stimuli in an Eriksen flanker task. The flanker interference was higher when the interval indicated low conflict proportions, which suggests that the interval can act as a contextual cue for attentional interference adjustment. Also, there is evidence that attention can be biased by implicit temporal regularities even when these regularities are uninformative about the target or irrelevant regarding the current task (Thomaschke et al., 2018; Yu & Zhao, 2015; Zhao et al., 2013).

The current study investigated whether implicit temporal regularities of distractor locations induce suppression that is tuned to the time at which the distractor is likely to appear. We used the additional singleton paradigm and presented the search display after a variable interval. The moment in time that the display was presented was predictive of the impending high probability distractor location. If individuals are sensitive to the implicit spatiotemporal distractor regularities, attentional capture should be reduced when the distractor occurs at the high probability location at the expected moments in time.

Method

Participants

This study was approved by the Ethical Review Committee of the Vrije Universiteit Amsterdam. We recruited 35 participants (27 females, 20.51 ±4.60 years), who all gave written informed consent. In their experiment with spatiotemporal target regularities, Wagener and Hoffmann (2010; Experiment 3) observed an effect size of $\eta_p^2 = .35$. To observe such an effect with .80 probability and the α set of .05 in a two by two (Interval × Target Location) repeated-measures analysis of variance (RM-ANOVA), a sample of 18 participants was suggested by MorePower 6.4 (Campbell & Thompson, 2012). However, because the present study concerned the spatiotemporal regularities of distractors, we expected our effect size to be smaller, leading us to roughly double the sample size. A sensitivity power analysis showed that the sample size of 35 participants allows the detection of an effect of $\eta_p^2 = .20$ with .80 probability ($\alpha = .05$).

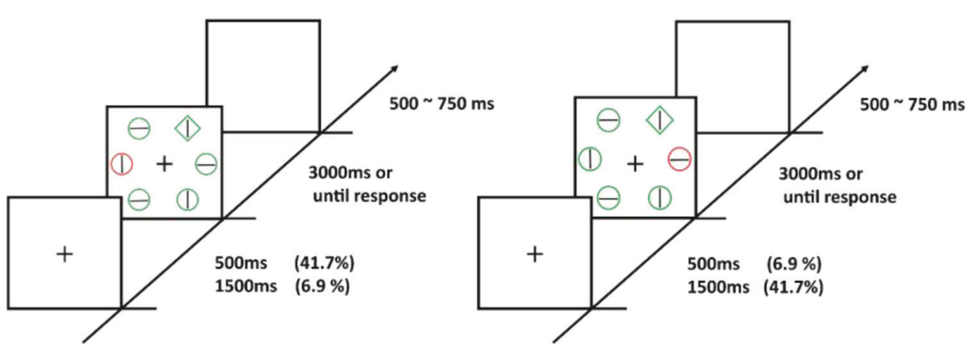
Apparatus

Participants were tested in the laboratory. The experiment was programmed in OpenSesame Version 3.2.8 (Mathot et al., 2012) and run on an HP Compaq Pro 6300 SFF computer with a 22-in. LCD color monitor (1680 × 1050 pixel resolution, 120 Hz refresh rate).

Procedure and Design

As shown in Figure 1, each trial started with a central white fixation cross (.8° × .8°) on a black background, which remained visible until the participant responded. After a delay of either 500 ms or 1,500 ms, the search display (six shapes presented on an imaginary circle with a radius of 4°) was presented for 3,000 ms

Figure 1
The Sequence of Trial Events



Note. Each trial started with a central white fixation cross on a black background (i.e., opposite colors are shown in the figure). After an equiprobable interval of either 500 ms or 1,500 ms, the search display was presented. Across trials with a short interval, the color singleton (i.e., red circles in the display) was more frequently presented at one of the high probability distractor locations (the left panel, high_500, 41.7%) whereas it was rarely presented at the opposite high probability distractor location (the right panel, high_1,500, 6.9%) and other four low probability distractor locations (low distractor condition, in total 18.1%). On the remaining trials, no distractor appeared (33.3%). The probabilities for high probability distractor locations were reversed for the long interval. Stimuli are not drawn to scale. See the online article for the color version of this figure.

or until response. The search displays consisted of either a circle (with a radius of 1°) among five diamonds (2.2° × 2.2°) or vice versa. Each shape had a red or green outline and there was a gray line inside it, which was oriented horizontally or vertically. Participants searched for the unique shape and responded to the orientation of the line inside using the "z" or "/" keys. When an error was made, a tone sounded. The intertrial interval was jittered from 500 ms to 750 ms.

Participants completed one practice block of 40 trials and six experimental blocks of 144 trials each. All conditions were randomized in each experimental block (Table 1). In 1/3 of the trials, all shapes were either all red or all green (no distractor condition) and the target appeared equally often at any one of the six locations. In the other 2/3 of the trials (distractor condition), one of the nontarget shapes had a unique color (the color singleton distractor). The color singleton could appear at any one of the six locations. However, two opposite locations were designated as high probability distractor locations. On any one distractor present trial, the target had an equal chance to occupy any one of the remaining five locations. This implies that, across all distractor present trials, the target was less likely to appear at either one of the high probability locations (~12 trials per block) than at any low probability location (~18 trials per block). However, this slight imbalance has been shown not to affect the influence of distractor suppression (Failing et al., 2019; Huang et al., 2021).

The interval between the onset of the fixation cross and the search display was equiprobably either 500 or 1,500 ms. Critically, these intervals were implicitly associated with either one of the high probability distractor locations. Across all trials with the short interval, the color singleton was more frequently presented at one of the high probability distractor locations (high_500, 41.7%) whereas it was rarely presented at the opposite high probability distractor location (high_1,500, 6.9%). Across all trials with the long interval, these probabilities were reversed.

At the end of the experiment, all participants were asked to indicate at which two locations they thought the color singleton distractors appeared most often and whether it occurred after a short or after a long interval.

Results

Trials with response time (RT) below 200 ms (.1%) were excluded. For RT analysis, incorrect responses (8.4%) were excluded. Subsequently, trials with RTs outside ±2.5 *SD* of the condition mean for each participant (distractor condition: 2.5%, target condition: .9%) were excluded. The Greenhouse–Geisser correction was applied whenever there was evidence for a violation of the sphericity assumption based on Mauchly's test. We also conducted Bayesian analyses in JASP .14 (JASP Team, 2020) with the default prior distribution of JASP. BF_{10} was calculated to quantify the evidence in favor of the alternative hypotheses over the null hypothesis.

Attentional Capture Effect

Figure 2 shows mean RT and accuracy (ACC) as a function of interval (500 ms, 1,500 ms) and distractor condition (high_500, high_1,500, low, no distractor). A RM-ANOVA on RT showed a significant main effect of distractor condition, $F(3, 102) = 57.825$, $p < .001$, $\eta_p^2 = .630$, but not a significant main effect of interval, $F(1, 34) = 2.845$, $p = .101$, $\eta_p^2 = .077$, $BF_{10} = .301$. The interaction between interval and distractor condition was significant, $F(3, 102) = 3.103$, $p = .030$, $\eta_p^2 = .084$. Post hoc tests using LSD correction indicated that when the search display was presented after the interval of 500 ms, participants responded quicker when there was no color singleton distractor compared with all other conditions (high_500 vs. no, $t(34) = 9.107$, $p < .001$, $d = 1.539$; high_1,500 vs. no, $t(34) = 8.091$, $p < .001$, $d = 1.368$; low vs. no, $t(34) = 10.791$, $p < .001$, $d = 1.824$), indicating a significant attentional capture effect. Also, compared with the low probability distractor condition, RT was significantly shorter for the high_500 condition, $t(34) = 5.501$, $p < .001$, $d = .930$, but not for the high_1,500 condition, $t(34) = 1.385$, $p = .175$, $d = .234$. There was a significant difference between the high_500 and the high_1,500 condition, $t(34) = 2.150$, $p = .039$, $d = .363$. When the search display was presented after the interval of 1,500 ms, there was a significant attentional capture effect (high_500 vs. no, $t(34) = 6.195$, $p < .001$, $d = 1.047$; high_1,500 vs. no, $t(34) = 8.623$, $p < .001$, $d = 1.458$; low vs. no, $t(34) = 10.644$, $p < .001$, $d = 1.799$). Compared with the low probability distractor condition, RT was significantly shorter when the color singleton distractor appeared at either the high_500, $t(34) = 2.123$, $p = .041$, $d = .359$, or the high_1,500 location, $t(34) = 4.395$, $p < .001$, $d = .743$. There was no significant difference between the high_500 and the high_1,500 condition, $t(34) = 1.070$, $p = .292$, $d = .181$.

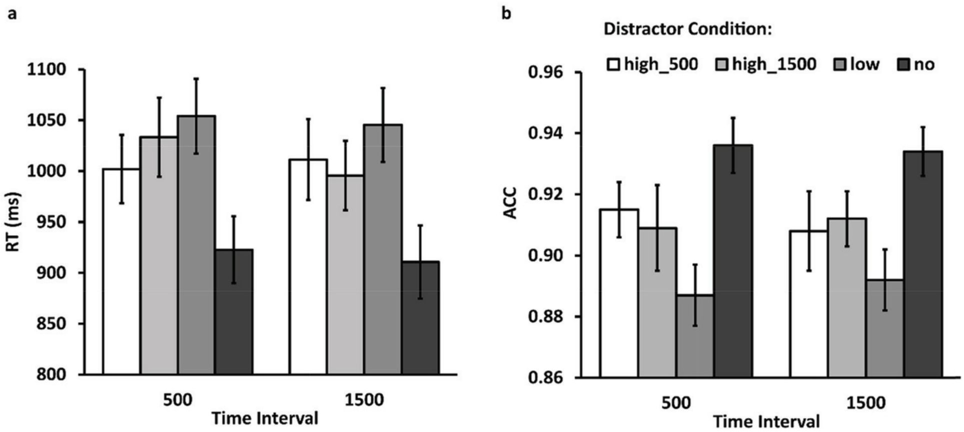
The analysis of ACC only revealed a main effect of distractor condition, $F(3, 102) = 19.265$, $p < .001$, $\eta_p^2 = .362$. No other effect was significant (see details in the online supplemental materials).

To determine whether suppression of high probability locations was specifically tuned to the moment in time in which participants had learned to expect the color singleton, we followed up with an ANOVA including only the high probability distractor condition (high_500, high_1,500) and interval (500 ms, 1,500 ms) as repeated measures (i.e., the two left-most bars for the 500- and 1,500-ms interval conditions in Figure 2a). The results of RT showed a significant interaction between interval and distractor condition, $F(1, 34) = 7.869$, $p = .008$, $\eta_p^2 = .188$. Post hoc tests using LSD correction indicated that after the interval of 500 ms, response was

Table 1
Trial Numbers of Each Condition in Each Experimental Block

Distractor condition	High_500	High_1,500	Low	No distractor	Total
Interval (ms)					
500	30	5	13	24	72
1,500	5	30	13	24	72
Total	35	35	26	48	144

Figure 2
Mean RT (a) and Mean ACC (b) as a Function of the Distractor Condition and Time Interval



Note. RT = response time; ACC = accuracy. Error bars represent ± 1 between-subject standard errors of the condition means.

significantly faster when the color singleton was presented at the expected high_500 location than when it was presented at the unexpected high_1,500 location, $t(34) = 2.150$, $p = .039$, $d = .363$. After the interval of 1,500 ms, there was no significant difference between the two high probability locations, $t(34) = 1.070$, $p = .292$, $d = .181$. Neither the main effect of distractor condition, $F(1, 34) = .423$, $p = .520$, $\eta_p^2 = .012$, $BF_{10} = .229$, nor the main effect of interval, $F(1, 34) = 1.528$, $p = .225$, $\eta_p^2 = .043$, $BF_{10} = .387$, was significant. The analysis of ACC revealed no significant effect (see details in the online supplemental materials).

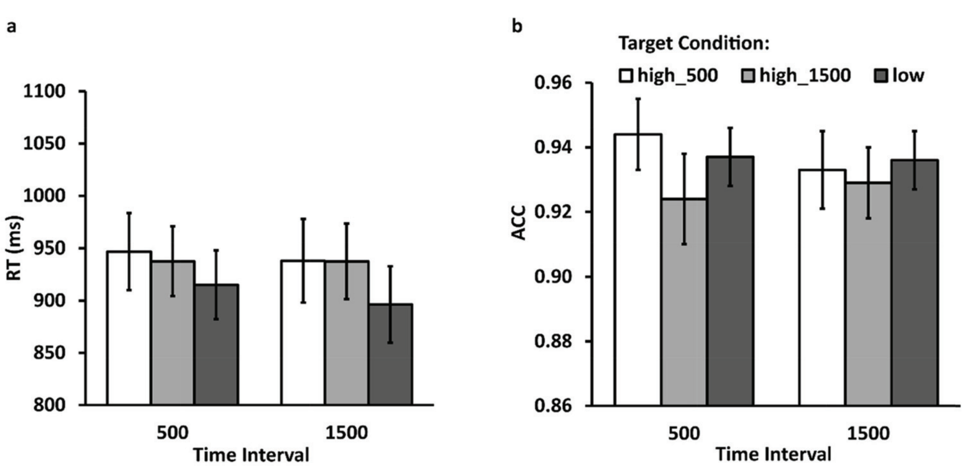
Target Selection in Singleton Absent Trials

To examine whether in the no distractor condition the efficiency of target selection was affected when the target happened to be presented at one of the high probability distractor locations, we performed a RM-ANOVA with interval (500 ms, 1,500 ms) and target condition (high_500, high_1,500, low) as factors (see Figure 3). On RT, the effect of target condition approached significance, $F(1.63, 55.26) = 3.251$, $p = .056$, $\eta_p^2 = .087$, $BF_{10} = 2.848$. There was no significant main effect of interval, $F(1, 34) = .710$, $p = .405$, $\eta_p^2 = .020$, $BF_{10} = .205$, and no interaction between the two factors, $F(1.64, 55.63) = .433$, $p = .611$, $\eta_p^2 = .013$, $BF_{10} = .102$. The analysis of ACC revealed no significant effects (see details in the online supplemental materials).

Awareness Assessment

To make sure that the revealed effects were not driven by the performance of participants that were aware of the regularities, we performed the same analyses mentioned above after excluding nine participants who correctly reported the two high probability

Figure 3
Mean RT (a) and Mean ACC (b) as a Function of the Target Condition and Time Interval



Note. RT = response time; ACC = accuracy. Error bars represent ± 1 between-subject standard errors of the condition means.

distractor locations, leaving a sample of 26 participants. Most importantly, a RM-ANOVA on RT with high probability distractor condition (high_500, high_1,500) and interval (500 ms, 1,500 ms) as factors also revealed a significant interaction effect, $F(1, 25) = 9.509$, $p = .005$, $\eta_p^2 = .276$ (see the online supplemental materials for further details). The results mimicked the above key findings, suggesting that being aware of the regularities did not play a critical role in obtaining the current results.

Intertrial Priming

To examine the extent to which our results can be explained as a propagation of intertrial location priming, we repeated the previous analyses after removing all trials in which the distractor location of the preceding trial was repeated (11.2% of the trials). A RM-ANOVA on RT with high probability distractor condition (high_500, high_1,500) and interval (500 ms, 1,500 ms) as factors revealed a significant interaction effect, $F(1, 34) = 6.585$, $p = .015$, $\eta_p^2 = .162$ (see the online supplemental materials for further details). Again, the results mimicked the above key findings, suggesting that the reported effects were not due to intertrial priming.

Discussion

The present study shows that attentional selection is tuned by the statistical regularities regarding distractors appearing in space and time. More specifically, attentional capture by a color singleton distractor was reduced when the distractor was presented at the high relative to the low probability location, suggesting suppression of these high probability locations. However, this suppression was even stronger when the color singleton was presented at the high probability location at its expected moment in time.

This temporal tuning of location suppression turned out to be asymmetric as it was clearly present at the 500-ms interval, but not at the 1,500-ms interval. As shown in Figure 2, at the 500-ms interval, the high_500 condition showed reduced interference relative to the low probability condition whereas the high_1,500 condition did not, which is consistent with the notion of temporal tuning of suppression. However, at the 1,500-ms interval, suppression was not only observed for the expected high_1,500 condition, but also for the unexpected high_500 condition. This asymmetric tuning effect can be explained by lingering suppression: Once a location is suppressed, it may remain in that state for some time. Thus, we assume that when the interval extends beyond 500 ms, the high_500 location remains in a suppressed state until the 1,500-ms interval is reached. By that time, the expected high_1,500 location has also becomes suppressed resulting in two locations being suppressed.[1]

Consistent with previous studies (Failing et al., 2019; Gao & Theeuwes, 2020; Wang & Theeuwes, 2018b), intertrial priming and awareness of the regularities could not account for current findings because the key results remained basically the same when trials with a repeated distractor location were excluded and when participants that showed some awareness of the high probability locations were excluded. This provides evidence that the effect is not attributable to conscious, top-down attentional control (Theeuwes, 2019; Wang & Theeuwes, 2018c). Inspired by exemplar based theories of long-term memory (Logan, 1988, 1990; Los et al., 2014, 2017, 2021), we propose that, as participants perform the task, a memory trace is created on each trial. Each memory trace contains information about where and when suppression was needed on that trial. On each new trial, these memory traces are jointly retrieved and shape the spatial priority map in a dynamical way as the trial unfolds. This would result in an implicit bias of attentional allocation in space and time, consistent with the present results.

Whereas we obtained evidence for time specific suppression of the distractor at the high probability locations, we did not obtain a corresponding suppression effect for the target when the target happened to be presented at the high probability location in singleton absent trials. The selection of the target was not significantly hampered when it happened to appear at one of the high probability distractor locations, which is in accordance with previous reports that the interference of target selection at the high probability distractor locations is not always reliable (Lin et al., 2021; Zhang et al., 2019). It is possible that the relative frequency of the high probability distractor condition relative to the low probability distractor condition was not high enough for inducing a significant target suppression effect (Lin et al., 2021; Zhang et al., 2019), let alone for its modulation in time.

The present findings may also help disambiguate several possible interpretations of previous findings in spatiotemporal SL. Previous studies associated two intervals with two target locations (Rieth & Huber, 2013; Thomaschke & Dreisbach, 2015; Wagener & Hoffmann, 2010), so that the observed SL effect could be explained by activation of the expected location, but also by suppression of the unexpected location. Therefore, the unequivocal emphasis in these studies on the allocation of attentional resources toward the expected location may be premature. The demonstration of the current study that interval regularities can tune the suppression of spatial locations invites a reconsideration of the explanation of those previous results.

In sum, the current study revealed an interaction between spatial and temporal regularities regarding the task-irrelevant distractor in visual attentional search, suggesting a conceivable spatiotemporal suppression mechanism in visual search.

[1] The probability that the distractor occurred at the high probability location after an incongruent interval (0.07) was higher than that it occurred at any one of the low probability locations (0.045). It should be noted, though, that the asymmetry of the suppression effect is not subject to this possible imperfection in the design because it was also observed in the analysis limited to the high probability conditions.

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Received October 19, 2020
Revision received March 2, 2021
Accepted March 5, 2021 ■