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Statistical Regularities Induce Spatial as well as Feature-Specific Suppression

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We are constantly extracting regularities from the visual environment to optimize attentional orienting. Here we examine the phenomenon that recurrent presentation of distractors in a specific location leads to its attentional suppression. Specifically, we address the question whether suppression is specific to the spatial regularities of distractors or also extends to visual features bearing statistical regularities. To that end, we used a visual search task with two high-probability locations, each showing one of two distractor types more often than the other. At these high-probability locations, target processing was impaired and attentional capture by either distractor was reduced, consistent with feature-unspecific spatial suppression. However, suppression was more facilitated when the distractor feature was presented at the high-probability location that matched its features, suggesting feature-specific suppression. Interestingly, feature-unspecific spatial suppression only spread between locations when distractors varied within a feature dimension (e.g., red and green) but not when they varied across feature dimensions (e.g., red and square). Our findings thus demonstrate a joint influence of implicitly learned spatial and feature regularities on attention and reveal how the visual system can benefit from complex statistical regularities.

Public Significance Statement
When we search the environment for relevant information, we are constantly trying to ignore irrelevant objects to avoid wasting cognitive resources when attempting to overcome distraction by them. To facilitate ignoring these distractors, we can learn to make use of the regularities they exhibit. Much of the research so far has focused on distractor regularities in space, showing that we can effectively suppress locations where distractors are likely to appear. Here, we investigated whether we also learn to use regularities in the visual features of distractors, such as their color or shape, to more easily ignore them. We found that efficient distractor suppression is based on implicit learning about regularities in both the visual features and the spatial position of distractors. Our results thus demonstrate that the visual systems can make use of complex regularities to optimize the distribution of cognitive resources.

Keywords: attention, statistical learning, attentional capture, distractor suppression

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Data from all experiments are available at https://osf.io/2qf5r/ and at https://github.com/MichlF/project-StatisticalRegularitiesInduceSpatialFeatureSpecificSuppression.

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Because of the vast amount of information in the environment and the limited capacity of the visual system, competition for visual processing arises. Visual attention is deployed to selectively prioritize and suppress information biasing competition such that the usage of the limited resources is optimized (Desimone & Duncan, 1995). This selectivity of attention is considered to be either driven by bottom-up mechanisms, that is, physical stimulus properties and their emergent salience (e.g., Theeuwes, 1992, 2010), or top-down mechanisms, that is, task-specific demands or goals (Folk & Remington, 2008; Leber & Egeth, 2006). Attentional control is furthermore determined by regularities in the visual environment. In essence, repeated exposure to stimuli creates, often implicitly, a learned selection bias that is shaped by associations of value, emotion valence, or other statistical regularities and acts independently of other top-down or bottom-up control processes on attentional control (Awh, Belopolsky, & Theeuwes, 2012; Failing & Theeuwes, 2018; Fiser & Aslin, 2002). The implication is then that learning processes enable competitive advantages for certain spatial locations and/or visual features by means of altering their priority for attentional selection.

Learning about the spatial regularities of a task-irrelevant distractor (i.e., how often it appears in a certain location of the visual field) in order to diminish its interference on searching for a target should give such a competitive advantage. However, the impact of spatial regularities in distractor presentation on attentional selection has been largely disregarded as most studies focused on regularities regarding the target location (e.g., Chun & Jiang, 1998; Geng & Behrmann, 2005). A recent study by Wang and Theeuwes (2018b) suggests that the exposure to regularities regarding a distractor location induces spatially selective suppression (see also Feldmann-Wüstefeld & Schubö, 2016; Ferrante et al., 2018; Goschy, Bakos, Müller, & Zehetleitner, 2014). In their study, participants searched for a shape singleton (circle among diamonds or vice versa) while ignoring a task-irrelevant color distractor (red among green or vice versa). Critically and unbeknownst to the participants, the presentation of the distractor was biased such that it was more likely to appear in one specific location in the visual field. The presence of the distractor slowed response times (RT) suggesting that it captured attention involuntarily (Theeuwes, 1992). Importantly though, attentional capture was weaker when the distractor appeared in a high-probability location. Moreover, in the distractor absent condition, target selection was impaired when the target happened to appear in the location with a high distractor probability. This effect occurred even though almost all participants were unaware of the statistical regularities. The authors argued that the spatial regularities regarding the distractor created spatially selective suppression biasing attention away from that location. This learned suppression reduced distractor interference, but also impaired the selection of the target at that location.

Given the evidence for feature-specific processing in the brain and its role in attention (e.g., Maunsell & Treue, 2006; Olivers, Humphreys, & Braithwaite, 2006; Olivers & Watson, 2006), assessing the contribution of feature-specific processing to distractor suppression induced by statistical regularities is important for models of visual attention and statistical learning. Indeed, while it is feasible that suppression is solely based on space (the high-probability location is generally suppressed), it may also be specific to the features (red and green are suppressed in this location). In a follow-up study, Wang and Theeuwes (2018c) aimed to address this by presenting one feature more frequently than another (e.g., 60% green distractor and 40% red distractor) in each location, including the high-probability location. They found that both features were similarly efficiently suppressed, suggesting that distractor suppression is feature-unspecific and solely driven by spatial regularities (Wang & Theeuwes, 2018c; Experiment 3 and 4). However, feature-specific suppression may rely on disentangling feature and spatial regularities. That is, if salient distractors are repeatedly presented in one location while their feature regularities are identical across all locations, this location might solely receive spatial suppression because feature-specific suppression is simply not expedient.

In the present study, we disentangled the regularities in space and features by introducing a novel version of the statistical learning paradigm with two high-probability locations. Participants had to search for a singleton target, and, on distractor-present trials, ignore a singleton distractor. However, one feature was presented more frequently in one location and another feature was presented more frequently in a second location, whereas each feature appeared equally often across all trials. More specifically, in Experiment 1, a red distractor was more likely to appear in one location, while a green distractor was more likely to appear in another location. In Experiment 2, a color distractor (red or green) was more likely to appear in one location, while a shape distractor (square or circle) was more likely to appear in another location. Thus, in both experiments, the probabilities for each of the distractors to appear in a specific location were independently manipulated, whereas the overall probability for a distractor appearing in any of the two high-probability locations was kept constant. In contrast to previous studies, this allowed for suppression of one feature (e.g., red) to emerge in one location and suppression of another feature (e.g., green) to emerge in a different location. This in turn allowed comparing suppression of, for example, a red distractor in a red high-probability location, a green high-probability location or a low probability location. We hypothesized that if suppression is solely driven by spatial regularities, attentional selection at both locations should be equally strongly suppressed no matter which of the two distractors is presented. However, if suppression is affected by feature regularities, suppression should be facilitated when the distractor is presented in its own high-probability location relative to that of the other distractor. In Experiment 2, we assessed whether the putative feature-specific influence on suppression is confined to a single feature dimension (i.e., within color) or extends across multiple feature dimensions (i.e., color and shape).

Experiment 1

Method

Sample size estimation and participants. We estimated the sample size based on the results of Wang and Theeuwes (2018b) who reported an effect size of $\eta_p^2 = .74$ for their main manipulation of the distractor's spatial probability. Using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007), an estimated sample size of 18 was necessary to obtain a similar effect for a power estimate of .95. However, we assumed that a feature-specific effect may not have the same effect size and thus went with a more conservative approach of being able to detect a true effect with the size of $\eta_p^2 =$

.5 at .95 probability. This approach resulted in an estimated sample size of 36. To complete all counterbalancing schedules, 48 volunteers (39 female, age $M = 21.6$) with reported normal or corrected-to-normal vision and naïve as to the study's purpose participated in Experiment 1. The experiment was approved by the local ethics committee of the Vrije Universiteit Amsterdam and informed consent was obtained before any experimental procedure began. All participants received either monetary compensation or course credits in exchange for participation.

Apparatus and stimuli. All stimuli were created using OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) and presented on a uniform black background (~0 cd/m^2) at a distance of 75 cm. A gray fixation cross was visible throughout each trial. The search display contained eight outline shapes which were, depending on the condition, either all gray or all gray except for one shape that was colored in any one of three isoluminant colors (red; RGB: 179/0/0; green; RGB: 0/123/0; or blue; RGB: 0/0/255; ~14 cd/m^2). For each participant, two (color 1 and color 2) out of these three colors were used. For example, for one participant, the colored shape could be either red or green, but never green (counterbalanced across participants). The shapes were presented on an imaginary circle at equal distance (4.75° visual degrees radius). Each search display contained exactly one shape singleton which was either a diamond (1.35°) among circles (1.1°) or vice versa. Within each shape was a line segment (0.75°) which had either one of two orientations (horizontal or vertical).

Procedure and design. Each trial consisted of a fixation display and a search display. The fixation display, visible at the beginning of each trial, was presented for a randomly determined period of 700 ms to 1,000 ms and followed by the search display for 2,000 ms or until response. Participants were instructed to indicate the orientation of the line segment inside the shape singleton ("target") on a keyboard (*K* for horizontal; *S* for vertical). Responses that timed out counted as incorrect. RT and accuracy feedback were provided at the end of each block.

Two design features were critical to this experiment: First, on one-sixth of the trials (distractor absent trials), all shapes in the search display were gray (see Figure 1A). On the remaining trials,

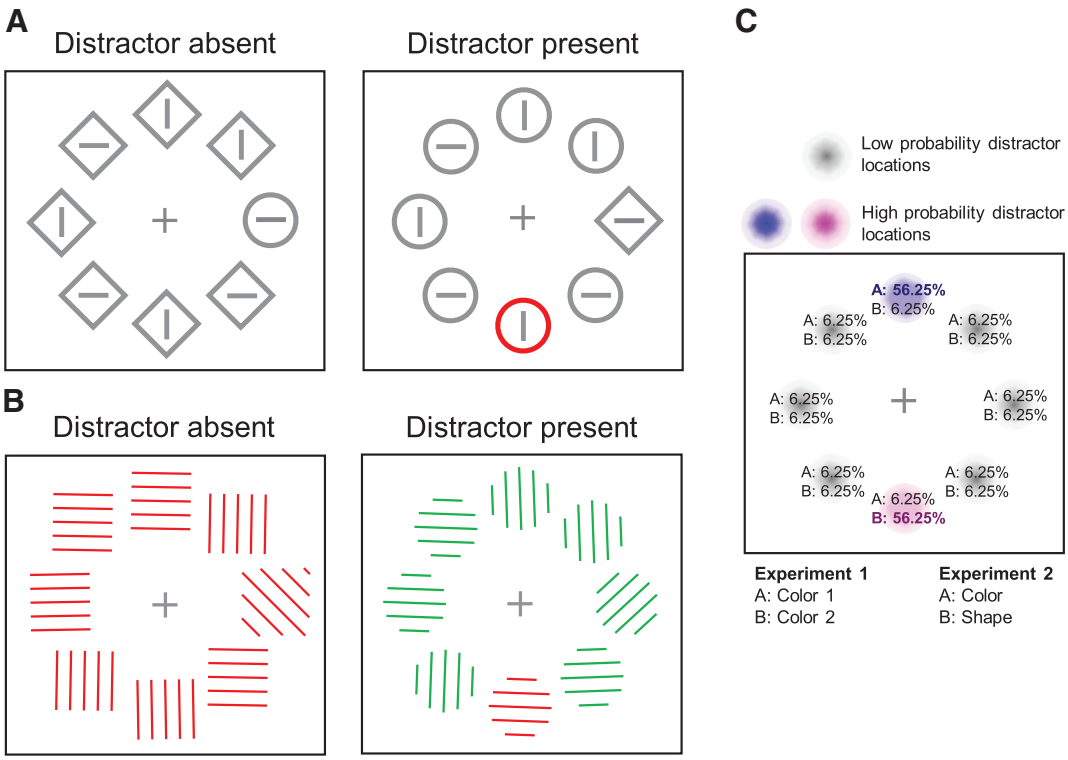


Figure 1. (A) Search display examples for Experiment 1. Participants had to search for a shape singleton and, on distractor present trials, ignore a color singleton distractor. The distractor in one color (e.g., red) was more likely to appear in one position along the imaginary circle (e.g., top position), while the distractor in another color (e.g., green) was more likely to appear in another position (e.g., bottom position). (B) Search display examples for Experiment 2: Participants had to search for an orientation singleton and, on distractor present trials, ignore either a shape or a color singleton. The color distractor was more likely to appear in one position along the imaginary circle (e.g., top position), while the shape distractor was more likely to appear in another position (e.g., bottom position). Note that the here shown Gabor patches are illustrations and not the actual stimuli. (C) Schematic representation of the spatial and feature regularities of the distractor. The two high-probability distractor locations are shown in purple and pink, and the low probability distractor locations are shown in gray. Percentages at each location represent the probabilities of each distractor type to appear in a given location. See the online article for the color version of this figure.

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an additional singleton (distractor) was present in the display (distractor present trials) that deviated in color from all other items in the visual field. For example, for one participant, the color singleton distractor could be a green shape among red shapes on some trials, while it was a red shape among green shapes on other distractor present trials. Second, each of these two distractors was more likely (56.25% of the respective distractor trials) to appear in one of the eight positions in the search display (see Figure 1C). The high-probability location for one color was at maximum distance to the high-probability location of the other color (i.e., they were on the opposite sides of the imaginary circle). This high-probability distractor position pair was counterbalanced across participants. For one participant, for example, a red distractor was more likely to appear at the top position, while a green distractor was more likely to appear at the bottom position. When a distractor did not appear in its specific high-probability location, it appeared in any of the other remaining locations at equal probability (6.25%), including the high-probability location of the other distractor. Three different distractor position conditions follow from this design: the distractor appears in the location where its feature (e.g., red) is most probable to appear ("high-probability location feature match"), the distractor appears in the location where the other feature (i.e., green) is most probable to appear ("high-probability location feature mismatch"), or the distractor appears in any of the six remaining locations where no feature is most probable to appear ("low probability location"). The target, on the other hand, was equally likely to appear at any location on distractor absent trials. On distractor present trials, the target's position was randomly determined with equal probability for each location not currently occupied by the distractor.

Each participant performed one practice block of 20 trials and 12 experimental blocks of 192 trials each. Half of the distractor present trials featured a distractor in one color and the other half featured a distractor in the other color. The shape of the target and the orientation of the line segment were pseudorandomized at equal probability.

After performing the task, participants were required to answer three forced-choice questions as part of a final implicit learning questionnaire (see the online supplemental material). For the first question, they were informed that the distractors displayed certain regularities and were asked to indicate whether they had noticed a regularity. For the final two questions, they were explicitly told that one particularly colored distractor was more likely to appear in one, while the other particularly colored distractor was more likely to appear in another location of the search display. Following this information, they were asked to indicate the locations for both distractors separately.

Data analysis. All analyses in both experiments were done with JASP, an open source statistical package (JASP Team, 2018). For RT analyses, only correct responses were used and responses faster than 200 ms were discarded (<1% in both experiments) from all analyses. Note that reported p values for each within-subjects analysis of variance (ANOVA) are, if the assumption of sphericity was violated, Greenhouse-Geisser corrected even though unadjusted degrees of freedom are reported. Analogously, for t tests for which the assumption of normality was violated (Shapiro-Wilk), p values reflect the results of Wilcoxon signed-ranks test and effect size measurement is given by the matched rank biserial correlation (r_b).

Results

Attentional capture and suppression. To assess whether the salient singleton distractor interfered with target search, we submitted RT data to an ANOVA with distractor presence as factor (absent vs. present Color 1 vs. present Color 2). There was a significant main effect of distractor presence, $F(2, 94) = 80.84$, $p < .001$, $\eta_p^2 = .631$. RTs on distractor absent trials ($M = 842$ ms $\pm$ $SD = 133$) were significantly faster relative to when either distractor was present (Color 1: 876 ms $\pm$ 132; $t(47) = 10.298$, $p < .001$, $d = 1.486$; Color 2: 877 ms $\pm$ 128; $p < .001$, $r_b = .968$). There were no significant effects on error rate (all $p > .05$). This suggests that both distractors captured attention.

Next, we analyzed whether distractor presence interfered with target search in all three locations of interest. Relative to distractor absent trials, RTs were slower on trials in which the distractor was presented in a low probability location ($p < .001$, $r_b = 1$; 905 ms $\pm$ 133), the high-probability location of Color 1, $t(47) = 5.359$, $p < .001$, Cohen's $d = .774$, 868 ms $\pm$ 135 and the high-probability location of Color 2, $t(47) = 6.578$, $p < .001$, $d = .949$; 876 ms $\pm$ 129. Moreover, RT was slower for trials in which the distractor appeared in any of the low probability locations relative to when it appeared in either the high-probability location of Color 1, $t(47) = 7.299$, $p < .001$, $d = 1.053$ or Color 2, $t(47) = 6.814$, $p < .001$, $d = .983$. For all comparisons, error rate was either significantly ($p < .01$) or numerically ($p > .05$) higher in distractor present compared to distractor absent trials which shows that the RT differences were not the consequence of a speed–accuracy trade-off. These results provide evidence for suppression of both high-probability distractor locations. Although there is distractor suppression at these locations, performance is still impaired compared to baseline levels (i.e., distractor absent trials).

Having established that distractors can be generally more easily suppressed at high-probability locations, we next investigated whether there was color-specific suppression at these locations, for example, whether red distractors were more easily suppressed at the location with a high probability for red distractors (feature match trials). To this end, we submitted RT data to an ANOVA with factors of distractor position (high-probability location feature match vs. high-probability location feature mismatch vs. low probability location) and distractor feature (Color 1 vs. Color 2). There was a main effect of distractor position, $F(2, 94) = 43.284$, $p < .001$, $\eta_p^2 = .479$, but no main effect of distractor feature, $F(1, 47) = 1.705$, $p = .198$, or interaction, $F(2, 94) = 2.353$, $p = .124$. Planned comparisons revealed that RTs were significantly faster in feature match trials (863 ms $\pm$ 130) relative to feature mismatch trials (880 ms $\pm$ 134; $p < .001$, $r_b = .537$; see Figure 2A). The slowest RTs were observed when the distractor appeared in any of the low probability locations (905 ms $\pm$ 133; vs. high-probability location feature match: $p < .001$, $r_b = 1$; vs. high-probability location feature mismatch: $t[47] = 4.654$, $p < .001$, $d = .672$). A similar analysis on the error rate only showed a main effect of distractor position, $F(2, 94) = 22.56$, $p = .045$, $\eta_p^2 = .045$, but no main effect of distractor feature, $F(1, 47) = .521$, $p = .521$ or interaction, $F(2, 94) = .631$, $p = .497$. The error rate was lower in feature match trials (5.8% $\pm$ 3) compared with low probability trials (6.6% $\pm$ 4; $t[47] = 4.652$, $p < .001$, $d = .671$).

These findings highlight that the magnitude of suppression varies systematically depending on whether the feature of the

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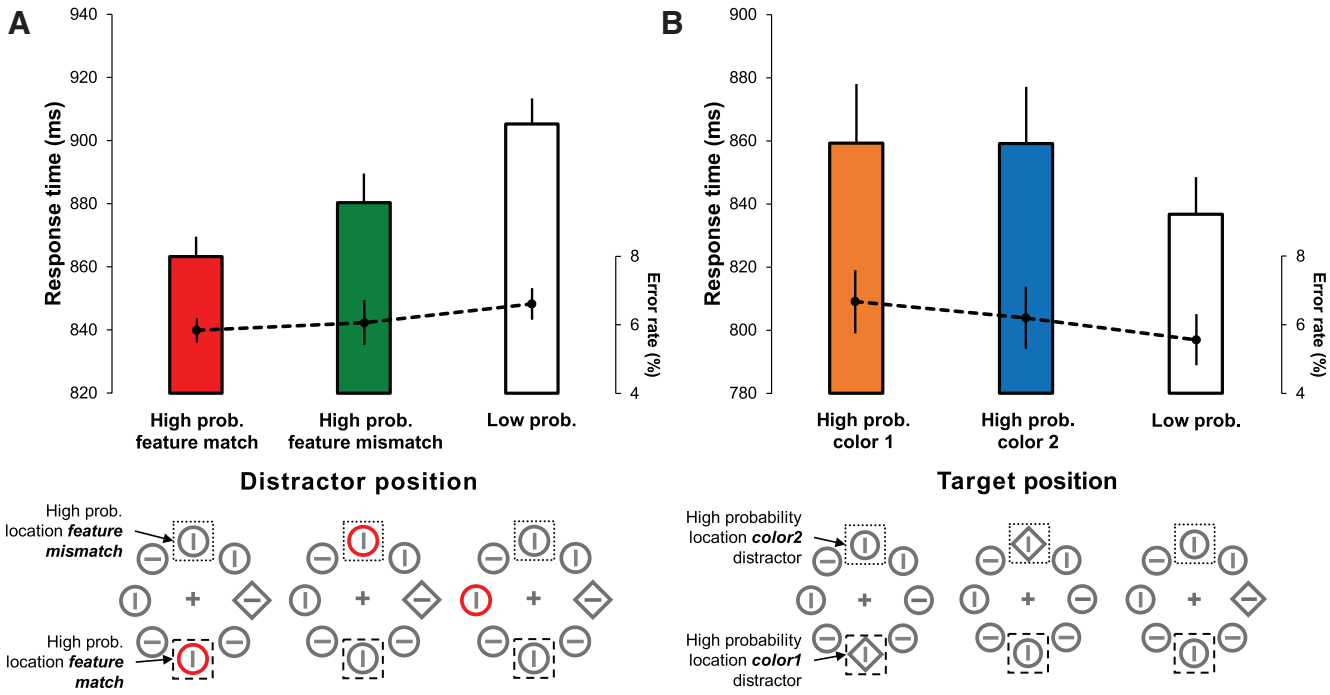


Figure 2. Results of Experiment 1. (A) Mean response time and error rate by distractor position for distractor present trials. Data is collapsed over different distractor feature conditions (i.e., red and green color singleton). The search display examples illustrate the different conditions using the red distractor condition. (B) Mean response time and error rate by target position for distractor absent trials. Note that the search display example for the low probability condition in each graph is an illustration of when the distractor (Panel A) or target (Panel B) appears in any low probability, not just the shown low probability location. Here and in all following figures, error rate is shown in the black dashed line and all error bars represent 95% within-subject confidence intervals (Morey, 2008). See the online article for the color version of this figure.

distractor matches with the feature that is highly probable for the distractor's position: When the distractor appears in the location where its feature is highly probable (e.g., the red distractor appears in the high-probability location of the red distractor) suppression is stronger compared with when it appears in the location where the feature of the other distractor is highly probable (e.g., the red distractor appears in the high-probability location of the green distractor).

Intertrial location priming. It is possible that the suppression is not the consequence of statistical learning of distractor location probabilities but instead due to short-lasting, intertrial location priming (Maljkovic & Nakayama, 1994). To test this alternative explanation for the observed differences in suppression, we submitted RTs of only the trials in which the position of the distractor in the previous trial was different to its position on the current trial to an ANOVA with distractor position as factor (high-probability location feature match vs. high-probability location feature mismatch vs. low probability location). There was a main effect of distractor position, $F(2, 94) = 43.51$, $p < .001$, $\eta_p^2 = .481$. Individual comparisons showed that even after removing all trials in which the distractor position repeated between trials, the earlier observed pattern remained robust and the effect equally strong: RT was faster in high-probability location feature match trials (867 ms ± 128) compared to high-probability location feature mismatch trials (885 ms ± 134; $t[47] = 4.170$, $p < .001$, $d = .602$) and low probability location trials (909 ms ± 133; $p < .001$, $r_b = .998$). RT in high-probability location feature mismatch trials was also significantly faster than low probability location trials, $t(47) = 4.525$, $p < .001$, $d = .653$. This shows that the suppression effects cannot be explained in terms of intertrial location priming.

Attentional suppression in the absence of the distractor. To investigate whether there was any evidence for suppression in the absence of the distractor, we assessed whether target search was affected when the target occurred in a high-probability distractor location in distractor absent trials. We ran an ANOVA on mean RT with the factor target position (high-probability location Color 1 vs. high-probability location Color 2 vs. low probability location) which showed a main effect, $F(1, 23) = 3.754$, $p = .037$, $\eta_p^2 = .208$). Planned comparisons revealed that RTs were shorter for targets appearing in any of the low probability locations (837 ms ± 133) than for targets appearing in the high-probability location of Color 1 (859 ms ± 136; $t[47] = 2.652$, $p = .011$, $d = .383$) or the high-probability location of Color 2 (859 ms ± 150; $t[47] = 2.814$, $p = .007$, $d = .406$; see Figure 2B). There was no significant difference between the two high-probability locations, $t(47) = .014$, $p = .989$, $d = .002$. There were also no significant effects on error rate (all $p > .05$). This shows that in the absence of a salient distractor, target processing is impaired when the target appears in either of the two high-probability locations.

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Spatial distribution of suppression. We further analyzed the spatial profile of the suppression by assessing how suppression changed as a function of the distance to the high-probability distractor locations (measured in number of positions). For this purpose, RT data of distractor present trials were submitted to an ANOVA with distance of the distractor to its feature matching high-probability location (0 to 4 positions). Distance 0 represent trials in which the distractor appeared in the feature matching high-probability location, distance 1 represents trials in which the distractor appeared next to that location and so on. Distance 4 thus represents trials in which the distractor appeared on the opposite side of the imaginary circle which is equivalent to being presented in the high-probability location that does not match the feature of the distractor. The analysis showed a main effect of distance, $F(4, 188) = 25.99$, $p < .001$, $\eta_p^2 = .356$, which exhibited a quadratic trend, $t(47) = 9.682$, $p < .001$. As is evident from Figure 3A, the fastest RTs were observed at the color-specific high-probability location (Distance 0) followed by a progressive increase in RT climaxing at the location that is the furthest away from both high-probability distractor locations (Distance 2). This peak was then followed by a modest reduction in RT toward the high probability of the other color (Distance 4). The pattern highlights a clear spatial gradient which mirrors the key features of the previous analyses: suppression of a distractor was most pronounced for the high-probability location that matched its feature and reduced but not completely abolished for the location where the feature of the other distractor was more probable. A similar analysis on error rate also revealed a significant main effect of distance, $F(4, 188) = 2.638$, $p = .047$, $\eta_p^2 = .053$, and a quadratic trend, $t(47) = 2.721$, $p = .007$. Error rates largely rose and fell with the changes in RT such that error rate was lower for both high-probability locations relative to the low probability locations.

For distractor absent trials, we ran similar analyses. Note that for this analysis, both high-probability locations were treated equally. An ANOVA revealed a main effect of distance, $F(4, 188) = 3.784$, $p = .012$, $\eta_p^2 = .075$, that exhibited a quadratic trend, $t(47) = 3.834$, $p < .001$. In line with the pattern expected for a spatial gradient in which both high-probability locations (i.e., of Color 1 and Color 2) are suppressed, RTs were the slowest for when the target appeared in one of the high-probability locations and progressively sped up the larger the distance to either of the two high-probability locations (see Figure 3B). The analysis on error rate also showed a significant main effect of distance, $F(4, 188) = 2.517$, $p = .049$, $\eta_p^2 = .051$, and a quadratic trend, $t(47) = 2.423$, $p = .016$, with error rate peaking for both high-probability locations.

Awareness of the relationship between distractor feature and location. To assess explicit knowledge about the statistic regularities, we used the results from the implicit learning questionnaire in which participants were asked whether they had noticed a relationship between distractor colors and positions. In this questionnaire, 30 participants reported that they had not noticed a relationship. Only five identified both relationships correctly (chance level: ~1.6% or one participant). After excluding the five

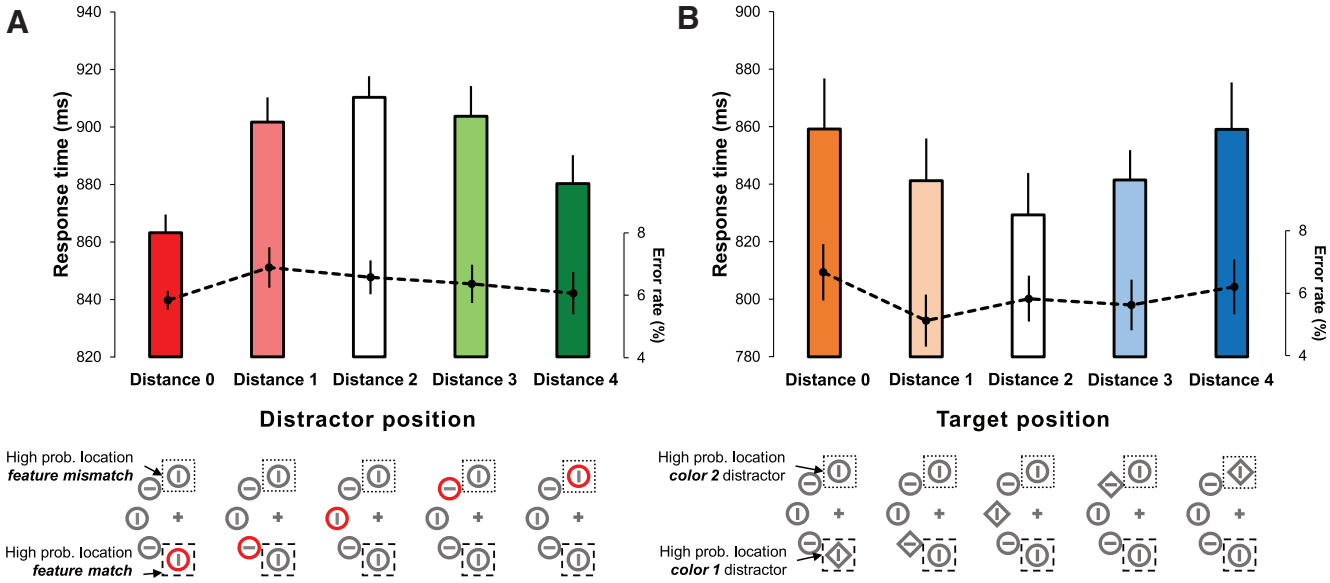


Figure 3. Results of Experiment 1. (A) Mean response time and error rate by distractor distance (0 to 4) to the high-probability distractor locations. Data is shown starting with trials in which the color singleton distractor appeared in the high-probability location that matched its feature (Distance 0) to trials in which it appeared in the high-probability location that did not (Distance 4). The search display examples illustrate the different conditions using the red distractor condition. (B) Mean response time and error rate by target distance to the high-probability distractor locations. Data is shown starting with trials in which the target appeared in the high-probability location of a one-color singleton distractor (Color 1; Distance 0) to trials in which it appeared in the high-probability location of the other color singleton distractor (Color 2; Distance 4). Data in both figures is shown collapsed across conditions in which distractor (Panel A) and target (Panel B) presentation were symmetric along the vertical meridian. See the online article for the color version of this figure.

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participants that indicated both relationships correctly from all analyses, the results from the main ANOVAs remained reliable.

Conclusions

In Experiment 1, we found evidence for spatially specific suppression: in the absence of a color singleton distractor, visual search was impaired when targets appeared in either of the high-probability locations, indicative of suppression of these locations. Similarly, distractor interference was reduced when any distractor appeared in any of the high-probability distractor locations. Crucially however, we also found evidence for feature-specific suppression: red distractors caused less interference in locations with a high probability for red than in locations with a high probability for green (and vice versa). In other words, when a distractor appeared in the high-probability location that matched its unique feature value, it interfered less with target search than when it appeared in the high-probability distractor location that did not match its unique feature value. This difference cannot be the consequence of differences in spatial regularities, as both high-probability locations were equally likely to contain a distractor. We can thus conclude that the extent of spatial suppression at a given location is contingent on the feature being presented at the location.

Finding evidence for spatial as well as feature-specific suppression has important implications for models of visual attention. Many attention models implement a hierarchy of topographic maps which reflect various stages of visual processing that correspond to feed-forward and recurrent connections (Fecteau & Munoz, 2006; Found & Müller, 1996; Itti & Koch, 2000, 2001). A core assumption are multiple feature maps, each representing a specific low-level quality of the environment (e.g., red hue or vertical orientation). The signals from the individual feature maps combine into dimension-specific conspicuity maps (e.g., a color conspicuity map receives input from red and green feature maps). These maps then feed forward dimension-specific conspicuity information to an overall saliency map which finally informs the priority map that determines the outcome of attentional selection (Fecteau & Munoz, 2006; Itti & Koch, 2000; Zelinsky & Bisley, 2015). Given this framework, the findings from Experiment 1 suggest that although suppression exhibits a strong feature-specific component such that suppression is specific to the location where the distractor feature is most probable (i.e., feature match trials), continuous suppression of one color at a given location can result in suppression of another color at the same location. This may be because suppression history spreads from feature maps to conspicuity maps (e.g., from red and green maps to the color map). Indeed, we found not only suppression for feature match trials, but also residual or lingering suppression for feature mismatch trials.

Experiment 2

In Experiment 1, we observed spatial as well as feature-specific suppression. Interestingly, we found evidence for spreading of suppression from one feature to another within a feature dimension. It is also important to assess whether this spreading is confined to a single feature dimension or can also occur from one feature dimension to another. In terms of attentional models, it is crucial to understand whether suppression can spread across conspicuity maps.

We addressed such putative dimension-specific components of suppression in Experiment 2 by using a color and a shape singleton rather than two color singletons. A color distractor was more likely to appear in one location, whereas a shape distractor was more likely to appear in another location in Experiment 2. If suppression spreads from one feature dimension to another, we would expect similar results as in Experiment 1. That is, both feature matching and mismatching trials should show evidence of suppression with feature matching trials showing the largest suppression. However, if the feature-specific suppression does not spread from one dimension to another, we would expect that there is only suppression of the distractor in the high-probability distractor location that matches its feature dimension.

Method

Participants. A new group of 48 volunteers (36 female, age $M = 24.81$) with reported normal or corrected-to-normal vision and naïve as to the study's purpose participated in Experiment 2.

Apparatus and stimuli. The experimental setup was identical to the first experiment with the following exceptions: the search display contained eight Gabor patches (2.15°) with a spatial frequency of .09 cycles/pixel and a random phase presented at equal distance to each other on an imaginary circle (5.5°). A Gabor could either have a circular or rectangular envelope and be of either one of two approximately isoluminant colors (red; RGB: 179/0/0; or green; RGB: 0/123/0; ~14 cd/m^2) with black troughs (~0 cd/m^2). In each search display, there was a Gabor that was an orientation singleton either tilted 45° clockwise or counterclockwise from vertical while the remaining Gabors were randomly tilted 2° clockwise or counterclockwise from vertical or horizontal.

Procedure and design. The procedure of the second experiment was identical to the first. However, in the second experiment, there were three feature dimensions: orientation, color and shape. The target was defined as an orientation singleton: participants were instructed to search for the Gabor that was 45° degrees tilted from vertical and indicate the direction of the tilt on a keyboard (slash for clockwise and backslash for counterclockwise; see Figure 1B).

Two design features were critical to the second experiment: First, on one-sixth of the trials (distractor absent trials), all Gabors had the same shape (i.e., envelope) and color. On the remaining trials, an additional singleton (distractor) was present in the display (distractor present trials). The distractor could equally often either be a color (equally often a red Gabor among green Gabors or vice versa) or a shape singleton (equally often a rectangular Gabor among circular Gabors or vice versa). Second, and identical to the first experiment, each of these two types of distractor (shape and color) was more likely (same probability as in Experiment 1) to appear in one of the eight positions in the search display with the constraint that both high-probability distractor locations had to be at maximum distance to each other (i.e., they were on the opposite sides of the imaginary circle; see Figure 1C). These high-probability distractor positions were counterbalanced across participants. Similar to Experiment 1, there were three distractor position conditions: the distractor appears in the location where its feature dimension (e.g., color) is most probable to appear ("high-probability location feature dimension match"), the distractor appears in the location where the other feature dimension (i.e., shape)

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is most probable to appear ("high-probability location feature dimension mismatch"), or the distractor appears in any of the six remaining locations where no feature dimension is most probable to appear ("low probability location").

Each participant performed one practice block of 25 trials and 13 experimental blocks of 192 trials each. Each fourth of the distractor present trials featured a green, red, rectangular or circular distractor respectively. The tilt of the target as well as nontarget Gabors was pseudorandomly determined at equal probability.

After performing the task, participants were required to answer three forced-choice questions as part of a final implicit learning questionnaire (see the online supplemental material). These were similar to those asked in Experiment 1.

Results

Attentional capture and suppression. To investigate whether both color and shape singletons interfered with target search, we submitted RT data to an ANOVA with distractor presence as factor (absent vs. color distractor vs. shape distractor). There was a main effect of distractor presence, $F(2, 94) = 80.95$, $p < .001$, $\eta_p^2 = .633$. RT on distractor absent trials (892 ms ± 177) was significantly faster compared to trials in which either the color distractor (912 ms ± 180; $t[47] = 4.133$, $p < .001$, $d = 0.597$) or the shape distractor was present (953 ms ± 183; $t[47] = 12.067$, $p < .001$, $d = 1.742$), although interference was larger on shape distractor trials than on color distractor trials, $t(47) = 8.596$, $p < .001$, $d = 1.241$. A similar analysis on error rate was nonsignificant, $F(2, 94) = 0.706$, $p = .471$, $\eta_p^2 = .280$. This shows that both distractor types capture attention.

Next, we analyzed whether distractor presence interfered with target search in all three locations of interest. Relative to distractor absent trials, RTs were slower on trials in which the distractor appeared in a low probability location (957 ms ± 183; $t[47] = 12.588$, $p < .001$, $d = 1.817$), the high-probability location of the shape distractor (934 ms ± 187; $t[47] = 6.836$, $p < .001$, $d = .987$) and the high-probability location of the color distractor (944 ms ± 186; $t[47] = 8.175$, $p < .001$, $d = 1.180$). In addition, RT was significantly slower in trials in which the distractor appeared in any of the low probability locations compared to when it appeared in either the high-probability location of the color, $t(47) = 2.362$, $p = .022$, $d = .341$, or the shape distractor ($p < .001$, $r_b = .709$). There were no significant differences in error rate (all $p > .1$). Similar to Experiment 1, these results provide evidence for suppression of both high-probability distractor locations. Again, although there is distractor suppression at both of these locations, performance is still impaired compared with baseline level (i.e., distractor absent trials).

Having established that distractors can be generally more easily suppressed at both color and shape high-probability locations, we examined whether there was dimension-specific suppression at the locations, for example, whether color singletons were more easily suppressed at the location with a high probability for color distractors (dimension match trials) compared to locations with a high probability for shape distractors (distractor mismatch trials). To this end, we submitted the RT data to an ANOVA with factors distractor position (high-probability location dimension match vs. high-probability location dimension mismatch vs. low probability location) and distractor dimension (color vs. shape). The ANOVA showed a main effect of distractor position, $F(2, 94) = 34.469$, $p < .001$, $\eta_p^2 = .423$, and distractor dimension, $F(1, 47) = 64.220$, $p < .001$, $\eta_p^2 = .577$, but no interaction, $F(2, 46) = 1.477$, $p = .234$. Planned comparisons revealed that RTs were significantly faster for high-probability location dimension match trials (919 ms ± 178) relative to high-probability location dimension mismatch trials (959 ms ± 194) or low probability location trials (957 ms ± 183; $t(47) = 6.589$, $p < .001$, $d = .951$ and $t(47) = 12.381$, $p < .001$, $d = 1.787$, respectively; see Figure 4A). Crucially however, there was no significant difference between high-probability location dimension mismatch and low probability location trials, $t(47) = .241$, $p = .811$, suggesting dimension-specific suppression. An analysis on error rate showed no significant effects (all $p > .1$).

These findings are consistent with feature-specific suppression: a distractor from a specific feature dimension is only suppressed when it appears in the location where a singleton distractor of its feature dimension is highly probable: suppression does not spread across feature dimensions.

Intertrial location priming. We also investigated whether the observed suppression effects in Experiment 2 may have been the consequence of short-lasting, intertrial location priming. We found that even after excluding trials in which the distractor position repeated between trials, the previously observed pattern of feature-specific suppression remained the same: an ANOVA on RT data with distractor position (high-probability location feature match vs. high-probability location feature mismatch vs. low probability location) showed a significant main effect, $F(2, 94) = 28.14$, $p < .001$, $np^2 = .375$, and further comparisons revealed that RT was significantly faster in high-probability feature match trials (921 ms ± 177) compared to either high-probability feature mismatch (958 ms ± 194; $t[47] = 5.607$, $p < .001$, $d = .809$) or low probability location trials (957 ms ± 183; $t[47] = 10.43$, $p < .001$, $d = 1.505$). There was no significant difference between RT of high-probability feature mismatch and low probability location trials, $t(47) = .156$, $p = .877$. This shows that, just like in Experiment 1, the observed feature-specific suppression in Experiment 2 is not the consequence of intertrial location priming.

Attentional suppression in the absence of the distractor. To examine the influence of the distractor regularities on target search in distractor absent trials, RT data was submitted to a one-way ANOVA with target position (high-probability location shape distractor vs. high-probability location color distractor vs. low probability location) as factor. This analysis revealed a main effect of target position, $F(2, 94) = 3.279$, $p = .042$, $\eta_p^2 = .065$. Planned comparisons showed that RT was faster when the target appeared in any of the low probability locations (883 ms ± 179) relative to when it appeared in either the high-probability location of the color distractor (919 ms ± 204; $p = .032$, $r_b = .355$) or the high-probability location of the shape distractor (926 ms ± 195; $t[47] = 3.185$, $p = .003$, $d = .460$; see Figure 4B). There was no significant difference between the two high-probability locations, $t(47) = .298$, $p = .767$, as well as no significant effects on error rate (all $p > .1$).

Spatial distribution of suppression. To further examine spatial specificity of the suppression effect, we analyzed how interference by the distractor varied as a function of the distractor's distance to its specific high-probability location. An ANOVA with distance of the currently presented distractor to its feature dimen-

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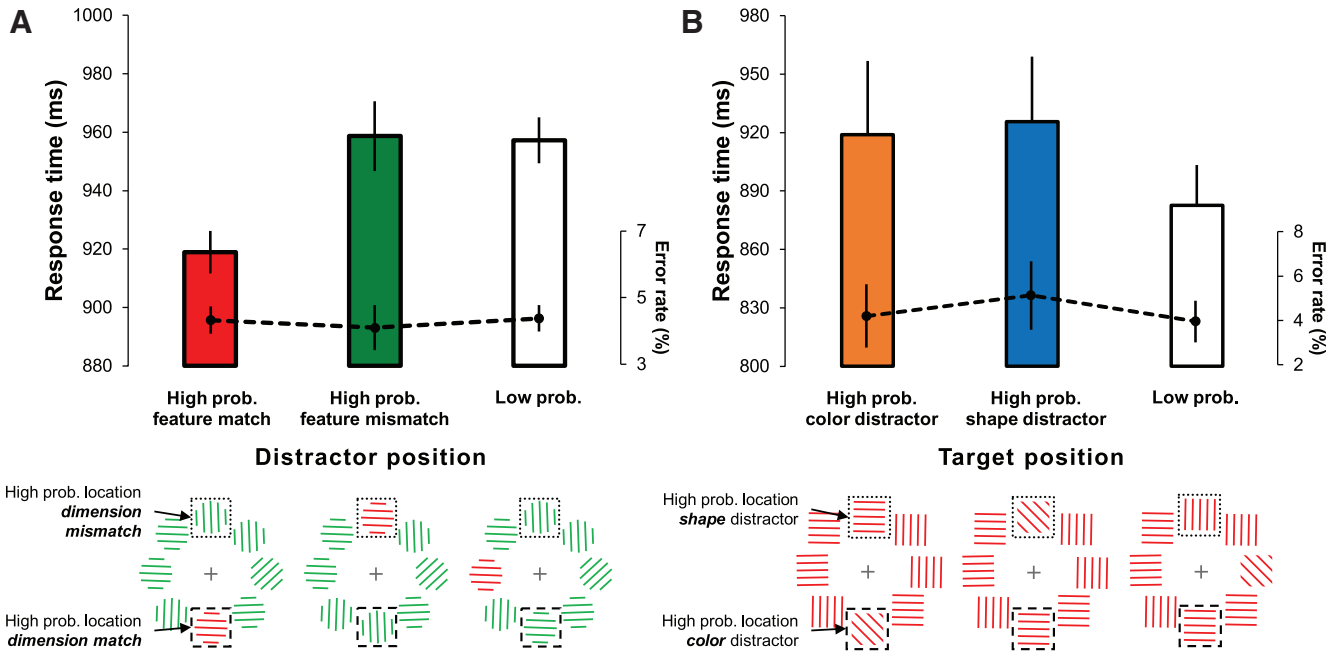


Figure 4. Results of Experiment 2. (A) Mean response time and error rate by distractor position condition for distractor present trials. Data is collapsed over different distractor type conditions (i.e., color and shape singleton) and the search display examples illustrate the different conditions using the color distractor condition. (B) Mean response time and error rate by target location for distractor absent trials. Note that the search display illustration for the low probability condition in each graph is an illustration of when the distractor (Panel A) or target (Panel B) appears in any low probability, not just the shown low probability location. See the online article for the color version of this figure.

sion matching high-probability location (0–4 positions) showed a main effect of distance, $F(4, 188) = 16.65$, $p < .001$, $\eta_p^2 = .262$, which exhibited a quadratic trend, $t(47) = 4.920$, $p < .001$. As is evident from Figure 5A, the fastest mean RTs were observed for the high-probability location that matched the feature dimension of the distractor followed by a progressive increase in RT the further away from that location. As in Experiment 1, this pattern shows a spatial gradient which mirrors the key features of the previous analyses: Suppression of interference was most pronounced at the high-probability location that matched the feature dimension of the distractor but completely abolished for the high-probability location that was a feature dimension mismatch. A similar analysis on error rate showed no significant effects.

For a similar analysis on distractor absent trials, the ANOVA revealed a main effect of distance, $F(4, 92) = 4.016$, $p = .013$, $\eta_p^2 = .079$, that exhibited a quadratic trend, $t(47) = 3.672$, $p < .001$. The pattern supported the previous analysis on distractor absent trials by showing a spatial gradient in which both high-probability locations are suppressed: RTs were the slowest for when the target appeared in one of the high-probability locations and progressively sped up the larger the distance to either of the two high-probability locations (see Figure 5B). There were no significant differences in error rate.

Awareness of the relationship between distractor dimension and location. In the implicit learning questionnaire, 29 participants reported to not have noticed a relationship between the distractors and locations. Furthermore, only a single participant correctly identified both relationships which is about chance level (~1.6% or one participant). After removing this participant from the analysis, the results of the main ANOVAs remained the same.

General Discussion

The two experiments reported here demonstrate an interaction of spatial and feature-specific processing in attentional suppression due to statistical regularities. Consistent with the notion of space-based distractor suppression (Burra & Kerzel, 2014; Feldmann-Wüstefeld & Schubö, 2013; Gaspar & McDonald, 2014), locations more often containing distractors were suppressed more than any other location. This was evident in impaired target processing at any of the high-probability distractor locations. In addition, distractor interference was reduced when the distractor appeared in any of the two high-probability distractor locations (Experiment 1) or the one that matched its feature dimension (Experiment 2) compared with low probability locations. Systematically biasing distractor presentation toward specific locations thus leads to spatial suppression. Spatial suppression, in turn, reduces attentional capture by salient distractors and impairs target selection at these locations (Ferrante et al., 2018; Wang & Theeuwes, 2018b, 2018c). These findings therefore fit well with the idea that capture by irrelevant feature singletons can be avoided through spatial inhibition, as recently put forward in the signal suppression hypothesis (Gaspelin & Luck, 2018; Sawaki & Luck, 2010) and are

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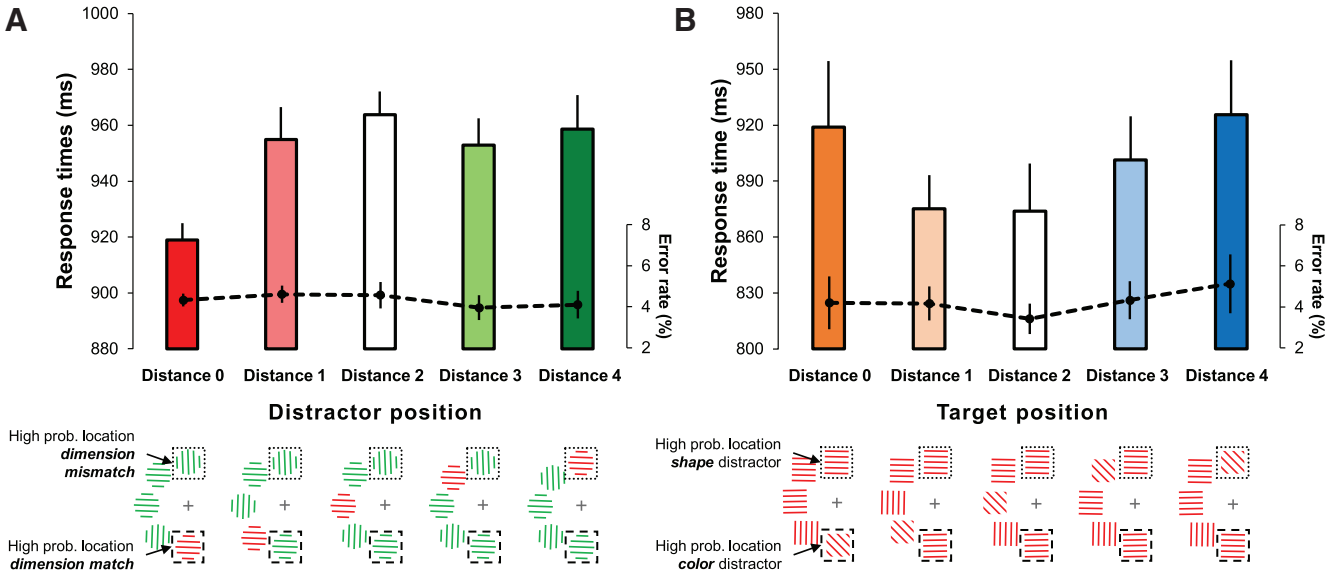


Figure 5. Results of Experiment 2. (A) Mean response time and error rate by distractor distance (0 to 4) to the high-probability distractor locations. Data is shown starting with trials in which the distractor appeared in the high-probability location that matched its feature dimension (Distance 0) to trials in which it appeared in the high-probability location that did not (Distance 4). The search display examples illustrate the different conditions using the color distractor condition. (B) Mean response time and error rate by target distance to the high-probability distractor locations. Data is shown starting with trials in which the target appeared in the high-probability location of the color singleton distractor (Distance 0) to trials in which it appeared in the high-probability location of the shape singleton distractor (Distance 4). Data in both panels is shown collapsed across conditions in which distractor (Panel A) and target (Panel B) presentation were symmetric along the vertical meridian. See the online article for the color version of this figure.

unlikely to reflect facilitated target processing at slightly more likely target positions (Failing, Wang, & Theeuwes, 2019).

Importantly, however, our findings support the notion that distractor suppression is selectively modulated due to statistical learning of feature regularities. This is evident when comparing conditions in which a distractor appeared in its specific (i.e., feature matching) high-probability location to when it appeared in the other (i.e., feature mismatching) high-probability location: interference by the distractor was reduced when it appeared in feature-matching locations in both experiments. This suggests more efficient suppression when a distractor is presented in a location where its feature is more probable. Analogously, recent findings show more efficient suppression of salient distractors when appearing in a frequent color compared to a less frequent color (Stilwell, Bahle, & Vecera, 2019; Won, Kosoyan, & Geng, 2019). In our Experiment 2, suppression in the feature-mismatching location was even so far reduced to be indistinguishable from suppression in low probability locations. These modulations were observed even after removing trial-by-trial repetitions of distractor locations demonstrating that they are not due to short-lived location priming. Instead, this suggests that spatial suppression due to the statistical regularities, experienced and integrated across multiple trials, can spread from one feature to another within a feature dimension (Experiment 1), but not across feature dimensions (Experiment 2). That is, the feature-specific modulation of suppression is evidently more difficult within a single feature dimension ("suppress only red, not green"), than across multiple feature dimensions ("suppress any color singleton, no shape singleton"). This is in line with the finding that specific suppression of feature dimensions is possible whereas suppression of specific features within a dimension is not (Feldmann-Wüstefeld, Uengoer, & Schubö, 2015).

The interplay of spatial and feature-specific processes in distractor suppression may be best accounted for by a two-step process. Past episodes of suppression lead to equally strong suppression of both high-probability distractor locations at the beginning of each trial. This preset suppression (Arita, Carlisle, & Woodman, 2012; Moher & Egeth, 2012) may already be active before the first feed-forward sweep of visual information (i.e., before the search display's onset). As the suppression of both locations was equally pronounced in the absence of any distractor, the preset suppression appears to be purely spatial. Following the onset of the search display, the presence of a salient distractor can trigger feature-specific processing which, in turn, allows for a selective modulation of spatial suppression. We speculate that the feature-specific processing is the mandatory consequence of an automatic processing of the singleton feature. The presence of a salient distractor might also trigger the instantiation of spatially and feature-specific memory traces of suppression of that feature which may ultimately be responsible for the here observed selective suppression effects.

Our findings have important implications for models of attentional control. Many attentional models implement a hierarchy of topographic maps. At the bottom of the hierarchy are feature maps, each being a spatial representation of a feature value (e.g., red hue

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or vertical orientation). The individual feature maps are summed into conspicuity maps for each feature dimension (e.g., color or shape) which are representations of how salient a location is in terms of an entire feature dimension. Via the saliency map, information from conspicuity maps is ultimately fed forward to an overall priority map that represent the summed input from all conspicuity maps weighted by top-down factors (Itti & Koch, 2000, 2001; Fecteau & Munoz, 2006; Zelinsky & Bisley, 2015). We extend this model by showing that history-driven feature suppression predominantly operates in a spatial manner (see Figure 6 for an illustration). When individuals continuously suppress a feature value at a given location, a history-driven suppression for this feature will be established at that location in the feature map (see the upper two rows in Figure 6). Suppression from the feature maps also spreads to their dimension-specific conspicuity maps (lowest row in Figure 6). In distractor absent trials, history-driven suppression is solely based on conspicuity maps, explaining why target processing is equally impaired at both high-probability location in both experiments (see Figure 2B and 4B). In other words, our experiments suggest that history-driven suppression occurs on (at least) two levels of the visual processing hierarchy: on the level of feature maps and conspicuity maps. We propose that the suppression at both of these levels is additive. For example, in Experiment 1, when a red singleton appears in the high-probability location for red, there is strong suppression due to coinciding suppression for that location on the red feature map as well as on the color conspicuity map. However, when a green singleton appears in the high-probability location for red, there is less pronounced suppression for that location because there is only suppression for that location on the color conspicuity map, but not on the green feature map (see Figure 6, left panel). According to the notion that conspicuity maps are neither connected to other conspicuity maps nor to feature maps from a different dimension (e.g., Itti & Koch, 2000), there should be no carry-over of suppression from one feature dimension to another. In line with this, we found no suppression when a distractor at a given location did not match the feature dimension that was most probable for this location (Experiment 2). It thus appears that consistent suppression of one color can, to some extent, facilitate the suppression of another color via common connections to the color conspicuity map. Yet, consistent suppression of a shape cannot facilitate the

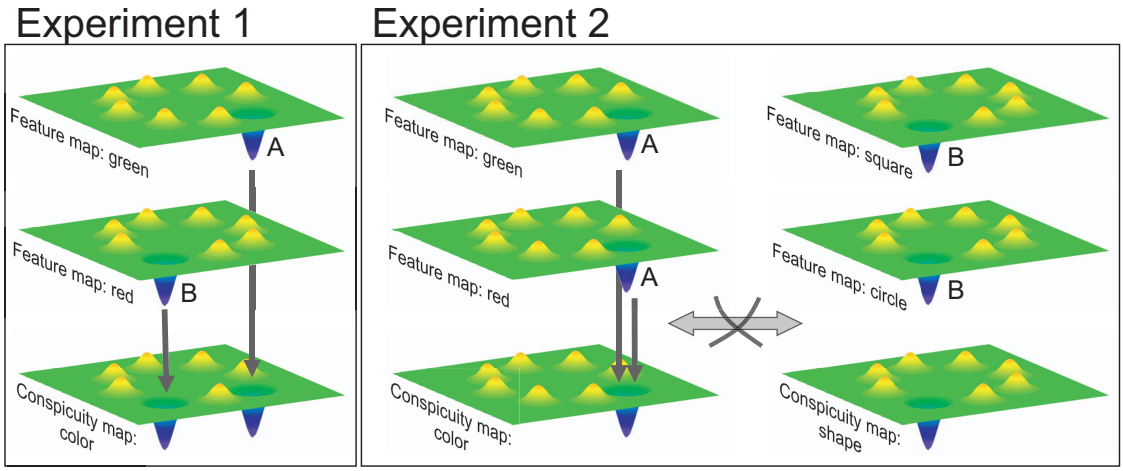


Figure 6. Illustration of history-driven suppression at the level of individual feature and conspicuity maps as a consequence of learning statistical regularities regarding distractor locations and features. Each map shows a retinotopic representation of selection priority. Peaks on this map represent spatial activation (in orange) and dips represent spatial suppression (in blue) as a consequence of the statistical learning process. Experiment 1: Biasing presentation of green distractors to location A resulted in a history-driven suppression at that location (upper panel). Analogously, Location B receives history-driven suppression due to biased presentation of red distractors at this location (middle panel). Suppression spreads from both feature maps onto the color conspicuity map (black arrows) resulting in suppression of both Locations A and B (lower panel) at the level of the color conspicuity map. Overall distractor suppression is the additive suppression from the feature map representing the distractor feature as well as the conspicuity map. Note that it is assumed that only the feature map representing currently present singletons will be activated. Accordingly, in red distractor present trials, for example, overall suppression is the sum of suppression from the red feature and color conspicuity map. In distractor absent trials, history-driven suppression is solely based on the conspicuity map. Experiment 2: The high-probability location within the feature dimension color is the same for green and red (Panel A) and within the feature dimension shape the same for square and circle (Panel B). As a result, suppression at both the feature maps (upper panels) and the dimension-specific conspicuity maps (lower panels) is confined to one location each. Because conspicuity maps of different feature dimensions are not connected (crossed out arrow in gray), suppression does not spread from one feature dimension to another. Suppression is thus entirely driven by the feature dimension of the currently presented distractor. Note that in the present experiments, high-probability locations were always presented on opposite locations. They are presented on the bottom of the maps in this figure for illustration purposes only. See the online article for the color version of this figure.

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suppression of a color (and vice versa) because their respective conspicuity maps are not connected.

The nature of the feature-specific modulations in spatial distractor suppression might be the consequence of a deliberate strategy much like feature-specific biasing due to top-down processes. However, given the lack of explicit awareness about the regularities in the display this seems rather unlikely (see also Wang & Theeuwes, 2018a, 2018b, 2018c). Moreover, when participants that correctly identified the statistical regularities were removed from the analysis, the same pattern of results was observed. This suggests that implicitly learned regularities rather than deliberate strategies explain the observed effects. Additionally, while it was beneficial to suppress high-probability distractor locations in our experiments, selectively suppressing one color at a given location was not more efficient than suppressing both high-probability locations equally as both were more likely to have a salient distractor than a target. Nevertheless, feature-specific suppression may not be a maladaptive mechanism but rather account for attentional suppression, much like enhancement, being a limited resource. Under real world circumstances, suppressing distracting feature information where it is likely to occur could be the most efficient strategy to optimize the use of limited suppression resources. Whatever the nature of the mechanism may be, it appears to be critical to maintaining flexibility in attentional control. A mechanism that selectively modulates spatial suppression may be the functional counterpart to an automatic and implicit learning system that is driven by the ubiquity of statistical regularities in the environment.

In short, it has recently been shown that implicitly learned regularities can induce spatial suppression for high-probability distractor locations. Here we show that this suppression is not solely due to spatial regularities but due to an interplay of spatial and feature-specific regularity information.

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Correction to Failing et al. (2019)

In the article, "Statistical regularities induce spatial as well as feature-specific suppression" by Michel Failing, Tobias Feldmann-Wüstefeld, Benchi Wang, Christian Olivers, and Jan Theeuwe (*Journal of Experimental Psychology: Human Perception and Performance*, Advance Online Publication, June 3, 2019, Advance Publication, http://dx.doi.org/10.1037/xhp0000660), Figure 1 was an older version and has been updated.

All versions of this article have been corrected.

http://dx.doi.org/10.1037/xhp0000701