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OBSERVATION

Statistical Regularities Modulate Attentional Capture

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The present study investigated whether statistical regularities can influence visual selection. We used the classic additional singleton task in which participants search for a salient shape singleton while ignoring a color distractor singleton. The color distractor singleton was systematically presented more often in 1 location than in all other locations. For this high-probability location, we found that both the amount of attentional capture by distractors and the efficiency of selecting the target were reduced. There was a spatial gradient of suppression, as the attentional capture effect and the efficiency of selecting the target scaled with the distance from the high-probability location. Some participants were aware of the statistical regularities, but this did not affect the results whatsoever. We interpret these findings as evidence that spatially statistical regularities that are unknown to the observer can influence attention such that locations that have a high probability of containing a distractor are suppressed relative to all other locations.

Public Significance Statement
The present study shows that spatially statistical regularities that are unknown to the observer cause an attentional bias that affects the amount of attentional capture by distractors and the efficiency of attentional selection of targets. We interpret these findings as evidence that the spatially statistical regularities influence attention such that locations that have a high probability of containing a distractor are suppressed relative to all other locations. Moreover, the location-based suppression we observed has a spatial gradient, as the attentional capture effect scaled with the distance from the high-probability location.

Keywords: attentional capture, bottom-up, suppression, location-based, statistical regularities

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When surfing the Internet, we typically try to find information that is relevant to us while ignoring flashing, supposedly salient banners presented along the side of the screen that try to capture our attention. When banners appear consistently at specific locations on the screen, we seem to be better able to ignore these images. The extent to which we are able to control attentional selection is one of the most debated issues in visual attention research (Theeuwes, 2010). Some researchers have claimed that salient events that are irrelevant to us can capture our attention despite our best intentions (Theeuwes, 1992, 2010); however, other researchers have claimed that capture is always mediated by top-down control (Folk, Remington, & Johnston, 1992).

The well-known additional singleton paradigm has been instrumental in the discussion regarding top-down and bottom-up control of attention (Theeuwes, 1991, 1992, 1994). In this paradigm, observers search for the target singleton while ignoring a distractor singleton. For example, observers searched for a green diamond presented among a varying number of green circles. In the distractor condition, one of these circles is red, creating an irrelevant distractor. Time to find the target typically increases when the irrelevant color singleton is present. On the basis of these findings, Theeuwes (1992) concluded that attention is captured automatically and involuntarily by the red singleton regardless of top-down control settings.

The basic notion of Theeuwes's (1992, 2010) stimulus-driven selection account is that when attention is divided across the visual field, processing is exclusively driven by the bottom-up properties of the stimulus field. After the initial analysis of a scene, one object is selected for further processing. If it is the target, then a response is given; if it is the distractor, attention needs to be shifted to the target in order to respond. It is assumed that initial selection is based on bottom-up factors such as salience (Theeuwes, 2010) or "acquired" salience through selection history (Awh, Belopolsky, & Theeuwes, 2012), specifically when particular stimulus features acquire reward value (e.g., Anderson, Laurent, & Yantis, 2011; Failing & Theeuwes, 2014).

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However, when selective attention is allocated more efficiently, the distracting effect of irrelevant information may be reduced. For example, Kelley and Yantis (2009) demonstrated that through practice, distracting information had less of an effect on performance and gradually generalized to other distractor locations. Others showed implicit attentional control due to statistical learning. For example, the efficiency of searching for a target can be improved when the target consistently appears at specific locations in previously seen displays relative to random locations (Chun & Jiang, 1999). Consistently cueing the target location and/or cueing the distractor location may result in an attentional suppression of that distractor location (e.g., Leber, Gwinn, Hong, & O'Toole, 2016; Munneke, Van der Stigchel, & Theeuwes, 2008). Moreover, targets presented in high-probability locations are detected faster than those in low-probability locations—an effect that could not be explained by repetition priming alone (Geng & Behrmann, 2005; Jiang, Swallow, Rosenbaum, & Herzig, 2013).

Instead of spatially cueing the target and/or cueing the distractor location, the target and distractor could appear anywhere in the display in the current study. Unbeknown to the observer, we consistently presented a distractor more often at one location than at other locations. The question was whether these spatial regularities would affect attentional selection and capture. Previous studies have shown that regularities improve the learning of object labels (Estes, Evans, Alibali, & Saffran, 2007) and facilitate object categorization (Turk-Browne, Scholl, Johnson, & Chun, 2010). Also, locations and features of objects embedded in temporal regularities may receive priority in visual searches (Zhao, Al-Aidroos, & Turk-Browne, 2013).

To determine the role of spatial regularities on capture and attentional selection, we used a variant of the classic additional singleton task in which observers search for a shape singleton (a circle between diamonds or a diamond between circles) while ignoring an irrelevant color singleton (either a green circle or a red circle presented among gray circles). Crucially, instead of presenting the distractor singletons evenly across the display, distractor singletons were presented much more often at one location (65% of the trials) than at all other locations (35% of the trials). The question was whether attentional capture was modulated for trials in which the distractor appeared at a high-probability location versus when it appeared at a low-probability location. If statistical regularities affect selection, attentional capture is expected to be reduced for trials in which the distractor appears at that high-probability location relative to the low-probability location. Moreover, in the no distractor condition when the target happens to be presented at this high-probability (distractor) location, observers are expected to have longer response times than when the target is presented at another location.

Method

This study was approved by the Ethical Review Committee of the Faculty of Behavioral and Movement Sciences of Vrije Universiteit Amsterdam.

Participants

Twenty-four adults (14 women with a mean age of 22.8 years) participated in this experiment. Before the study, all participants provided written informed consent. They reported normal color vision and normal or corrected-to-normal visual acuity.

Apparatus and Stimuli

Stimulus presentation and response registration were controlled by custom scripts written in Python run on an HP Compaq 8000 Elite computer with a 21-in. liquid crystal display (LCD) color monitor. In a dimly lit laboratory, participants held their chins on a chin rest located 71 cm away from the monitor. To ensure that participants maintained fixation, an EyeLink 1,000 eye tracker was used. Its spatial resolution was reported to be 0.2° or better, and the sampling rate was set to 1,000 Hz.

As illustrated in Figure 1, the primary experimental display contained a visual search array consisting of eight discrete stimuli with different shapes (one circle vs. seven unfilled diamonds or vice versa), with each shape containing a vertical or horizontal gray line (0.3° × 1.5°) inside. These stimuli were presented on an imaginary circle with a radius of 4° centered at the fixation (a white cross measuring 1° × 1°) against a black background (6 cd/m^2). The circle's radius was 1°, the unfilled diamond was subtended 2° × 2°, and each shape had a red or green outline.

Procedure and Design

A self-paced drift check was performed at the beginning of each trial. A fixation cross then appeared and remained visible throughout the trial. After 500 ms, the search array was presented for 3,000 ms or until the participant responded. Participants had to search for one circle (target) among seven diamonds (distractors), or vice versa, and indicate whether the line segment inside the target was vertical or horizontal by pressing the *up* or *left* key on the keyboard as soon as possible. The intertrial interval (ITI) was between 500 and 750 ms at random.

The target was present in each trial, and it was equally likely to be a circle or a diamond. A uniquely colored distractor singleton was used in 66% of the trials, with the same shape as other distractors but a different color (red or green with an equal probability). All conditions were randomized within blocks. The distractor singleton could be shown at eight locations from the imaginary ring with a 4° radius. However, one of these distractor

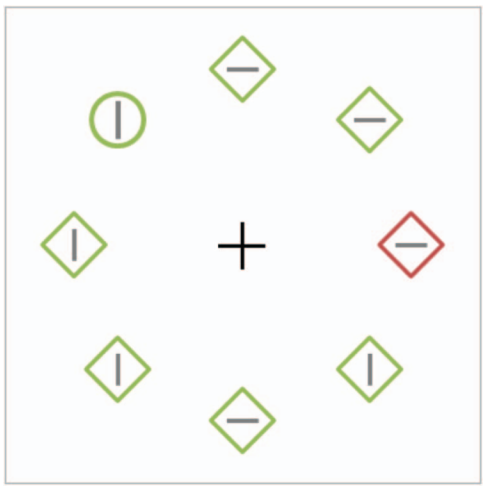


Figure 1. The display setup and possible target and distractor locations. See the online article for the color version of this figure.

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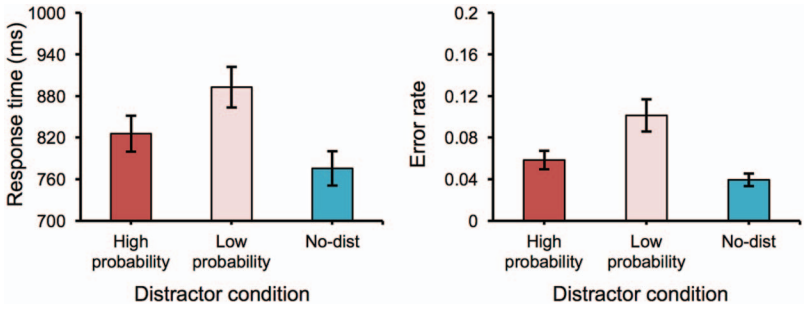


Figure 2. The mean response times (RTs; left panel) and the mean error rates (right panel) between different distractor conditions. Error bars denote ±1 the standard error of the mean. See the online article for the color version of this figure.

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locations had a high proportion of 65% (high-probability location; i.e., 43% of the total trial number), and other locations had a low proportion of 35% (low-probability location). The high-probability distractor location remained the same for each participant and was counterbalanced across participants. In the no distractor condition, the target appeared equally often at each location. Participants completed 40 practice trials and six blocks each containing 120 trials, and they were required to remain fixated on the center of the display throughout the trial. Warning messages were presented if the participant's gaze deviated more than 2° from fixation, if he or she did not respond, or if he or she pressed the wrong key. Trials with larger gaze deviation were later retested in a random order until all trials were completed successfully.

Results

Trials on which the response times (RTs) were slower than 2,000 ms (1.45%) were excluded from analyses.

Attentional Capture Effect

Mean RTs and mean error rates are presented in Figure 2. A one-way analysis of variance (ANOVA) on mean RTs with the distractor condition (high-probability location, low-probability location, and no distractor) as a factor showed a main effect, $F(2, 46) = 130.9$, $p < .001$, $\eta_p^2 = .85$. Subsequent planned comparisons showed that there were significant attentional capture effects for a distractor presented at the high-probability location, $t(23) = 8.03$, $p < .001$, and the low-probability location, $t(23) = 13.67$, $p < .001$. Crucially, however, there was also a reliable difference between the high- and low-probability locations, $t(23) = 9.82$, $p < .001$, suggesting that the attentional capture effect was reduced for trials in which the distractor appeared at a high-probability location. The error rate results mimicked those for RTs (see the supplemental material).

Target at the High-Probability Distractor Location

To determine not only whether attentional capture was affected but also the efficiency of selecting the target, we examined RTs in the no distractor condition. We expected that even when the distractor was absent, observers would respond more slowly toward a target singleton when it was presented at the high-probability distractor location relative to the low-probability location. This is exactly what we found (see the left panel of Figure 3): Participants were slower to respond when the target was presented at the high-probability distractor location rather than at the low-probability distractor location, $t(23) = 2.73$, $p = .012$. There was no effect on error rates ($t < 1$).

The Spatial Distribution of the Suppression Effect

We examined RTs and error rates of the target when the distractor singleton appeared at different locations in relation to the distance from the high-probability distractor location. If the effect has a spatial extent, the response time (RT) and the error rate are

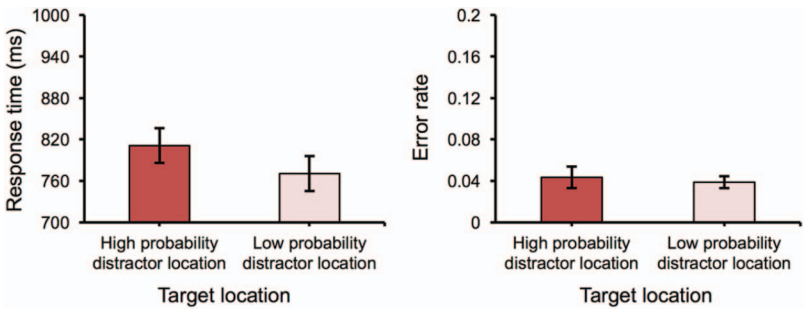


Figure 3. The mean response times (RTs; left panel) and the mean error rates (right panel) in the no distractor condition. Error bars denote ±1 the standard error of the mean. See the online article for the color version of this figure.

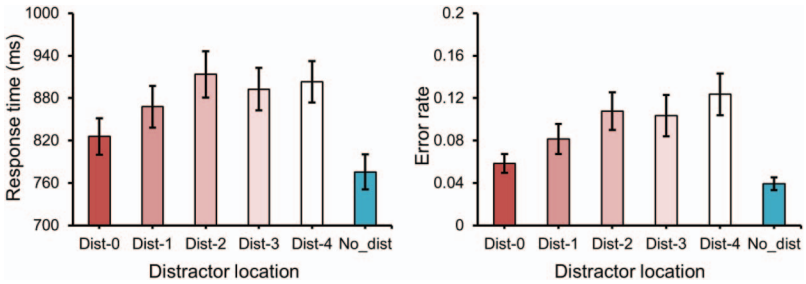


Figure 4. The spatial distribution of attentional capture effect by the means of response times (RTs; left panel) and error rates (right panel). Here, *Dist-0* refers to the high-probability distractor location, *Dist-1* refers to the low-probability distractor location with one unit (45° polar angle) away from the high-probability distractor location, and so on. Error bars denote ±1 the standard error of the mean. See the online article for the color version of this figure.

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expected to scale with distance from this area. Thus, the distractor location was divided into five distances (dist-0, dist-1, dist-2, dist-3, and dist-4)[1] from the high-probability distractor location. The mean RTs and mean error rates for these conditions are presented in Figure 4. A one-way ANOVA on mean RTs showed a significant main effect for distance, $F(4, 92) = 14.49$, $p < .001$, $\eta_p^2 = .39$. Moreover, we fitted the data with a linear function and used its slope to determine whether RT changed with distance. The slope (17.81 ms per display element) was significantly larger than zero, $t(23) = 5.73$, $p < .001$, suggesting a spatial gradient (the distractor effect grew when the distractor was presented farther away from the high-probability distractor location). The same effects were found for error rates (see the supplemental material).

In the no distractor condition, there was also a significant main effect for distance, $F(4, 92) = 4.57$, $p = .002$, $\eta_p^2 = .17$. The gradient effect was now reversed: With increased distance, the selection of the target became progressively more efficient, signified by a slope of −9.82 ms per display element that differed from zero, $t(23) = 2.2$, $p = .038$. This latter effect suggests spatial suppression that is not dependent on whether or not a distractor is present.

Additional analyses can be found in the supplemental material. The results show that the suppression effect and its observed spatial distribution were not the result of practicing to overcome distraction or due to the short-term location-based priming of the distractor location; the spatial distribution of the suppression effect was already present in the first block.

Intertrial Distractor Effects

If the reduced capture at the high-probability distractor location is purely location based, it can be expected that it does not matter whether the color of the distractor presented at the high-probability distractor location is repeated from the previous trial to the next. However, if the feature-based effect rides on top of a location-based effect, it can be expected that when the color of the distractor presented at the high-probability distractor location is repeated, the effect is stronger than when it is not repeated. There was no difference for RTs and error rates when the color of the distractor presented at the high-probability distractor location is repeated or not (both ts < 1), suggesting that feature-based attention does not play a role in this type of location-based suppression (see Figure 5).

Awareness of Statistical Regularities

To determine whether participants were aware of the statistical regularities, 32 new participants were recruited to replicate the current experiment with only four blocks. Following the experiment, participants were asked to indicate the location that they thought contained the distractor most often and how confident they were of their answers (scaled from 1 to 7). Seventeen participants chose the wrong location. Of the 15 participants who indicated the correct location, only five participants were sure about their answers, whereas 10 participants were basically guessing (i.e., they had a confidence score less than the mean).

Furthermore, we analyzed the results separately for those who correctly identified (mostly guessed) the location and for those who chose the wrong location as a between-subjects variable. There was no effect of group, nor any interaction with the other variable (see the supplemental material), indicating that some awareness of knowing the high-probability location did not alter the results.

Discussion

The present study shows that statistical regularities regarding the location of distractors can influence visual selection. We show that these regularities affect both attentional capture by the distractors and the efficiency of selecting the target. Attentional capture by a salient singleton presented at a location that is more likely to contain a distractor was reduced relative to capture by a singleton presented at other locations. Moreover, if a target singleton happened to be presented at this location, its selection was less efficient than when the target singleton was presented at other locations.

We interpret these effects as evidence that statistical regularities influence attention in such a way that the location that has a higher probability of containing a distractor competes less for attention

[1] The dist-0 location refers to the high-probability distractor location; the dist-1 location means that the distractor was presented next to the high-probability distractor location (45° polar angle); the dist-2 location refers to 90° from the high-probability distractor location; the dist-3 location refers to 135° from the high-probability distractor location; and the dist-4 location refers to 180° from the high-probability distractor location.

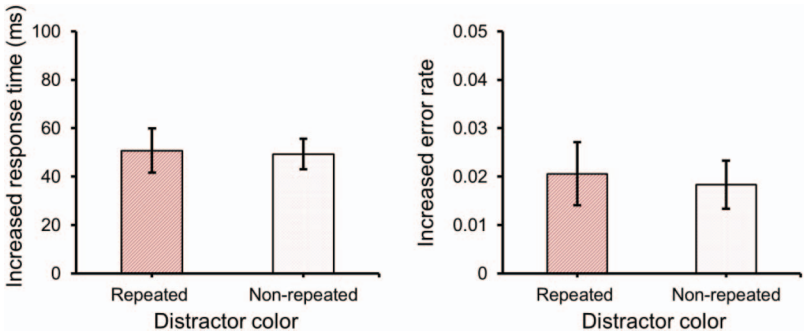


Figure 5. The attentional capture effect on response times (RTs; left panel) and error rates (right panel) in the high-probability distractor location. Error bars denote ±1 the standard error of the mean. See the online article for the color version of this figure.

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than other locations. We assume that this location is suppressed relative to other locations, as there was a spatial gradient effect for both the distractor (the closer to the suppressed location, the less capture was observed) and the target (the closer to the suppressed location, the less efficient target selection was). Moreover, whether or not the distractor color at the suppressed location was repeated from one trial to the next had no effect on capture, suggesting that the observed suppression was not feature based.

Previous contextual cueing studies (e.g., Chun & Jiang, 1999) have shown that repeated exposure to a configuration of objects improves the efficiency of visual search. Crucially, these contextual cueing effects seem to occur implicitly, and outside awareness as a direct test of explicit knowledge showed small, if any, effects. This is consistent with the results of our additional experiment, which demonstrated that most observers are unaware of the high-probability distractor location. Also, the awareness of that location (if it existed) did not alter the results whatsoever. This indicates that the suppression is not due to conscious control nor top-down strategy. Instead, these effects are assumed to be the result of effects of recent attentional deployments (i.e., selection history) eliciting lingering selection biases (e.g., Awh et al., 2012). We assume that within the priority map, the high-probability distractor location is suppressed relative to other locations such that items appearing at that location compete less for attention than items at all other locations.

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