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Does It Help to Expect Distraction? Attentional Capture Is Attenuated by High Distractor Frequency But Not by Trial-to-Trial Predictability

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Salient distractors such as color singletons typically capture attention. Recent studies have shown that probabilistic expectations of color singletons' occurrence—even when their location and features are unpredictable—can eliminate attentional capture. Here we ask whether this effect, referred to as "second-order distractor suppression," (a) could be merely a result of repetition priming, and (b) is also observed when distractor occurrences are predictable within a sequence of trials? Experiment 1 introduces a novel approach for manipulating the frequency of distractor occurrence while controlling for intertrial priming *by design*, by embedding identical trial sequences in the to-be-compared conditions. We observed no elimination but significant attenuation of capture in the condition with a higher distractor frequency. In Experiments 2 and 3 we investigated the effect of the trial-to-trial predictability of distractor presence. Repeating regular distractor absent/present patterns did not result in attenuated capture compared with a random condition, not even when upcoming distractor presence was cued. Taken together, the results demonstrate that second-order distractor suppression is not merely a result of repetition priming. However, it is not a response to any type of expectation; this nonspecific type of suppression is almost instantly elicited by environments characterized by a high likelihood of distractors but not by distractor presence that can be anticipated on a trial-by-trial basis.

Public Significance Statement

Does it help to expect distracting, task-irrelevant stimuli even if we do not know what a distractor will look like or where it will appear? This study investigated how the frequency of singleton distractors, their occurrence within a predictable sequence, and explicit cues regarding distractor presence in an upcoming display affect attentional capture. It used a novel experimental approach to tightly control intertrial effects. The results suggest that humans are able to very promptly adopt a nonspecific distractor suppression mode (resulting in attenuated attentional capture) upon entering contexts where task-irrelevant distracting stimuli are highly frequent. This same type of suppression is not elicited when the presence of a distractor in an upcoming search display is predictable given the preceding trial sequence, not even with the addition of a cue that explicitly indicated distractor absence or presence. This work highlights the importance of differentiating between different types of statistical regularities (a distribution vs. a trial-to-trial sequence) that could lead to the formation of expectations regarding distraction and modulate attentional capture.

Keywords: attentional capture, distractor suppression, visual search, frequency, predictability

Navigating the visual world, we usually aim to focus on information that is relevant to us while ignoring distracting task-irrelevant information. And yet, certain physically salient stimuli, such as a red object in an otherwise green environment or a blinking light, have long been known to capture observers' attention regardless of their relevance (e.g., Jonides & Yantis, 1988; Theeuwes, 1993). The extent to which attentional capture occurs in an automatic fashion independent of the observer's current goals, is one of the most debated issues in the field of attention research (e.g., Folk & Remington, 2010; Theeuwes, 2010). Nonetheless, voices from the different sides of the debate now seem to agree that while salient stimuli automatically produce a priority signal, the capture of attention by such stimuli can be reduced or even prevented via inhibitory mechanisms (Luck et al., 2021).

Recent research shows that the probable characteristics of recurring distractors can be (implicitly) learned, effectively attenuating the impact of distractors. This holds for different types of statistical regularities. For example, a series of studies using the additional singleton task (Theeuwes, 1992) demonstrated that spatial locations that have a high probability of containing a singleton distractor get suppressed. This reduces interference from distractors when presented at this location while increasing response times

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when the target happens to appear on the high probability distractor location (e.g., Ferrante et al., 2018; Wang & Theeuwes, 2018). Behavioral and electroencephalogram (EEG) evidence supports the notion that this type of spatial suppression is already evident before display onset and is proactive in nature (Huang et al., 2021; Wang et al., 2019). Rather than being distributional in nature (i.e., one more location being more probable), statistical regularities can also take the form of regular across-trial sequences. Recent findings show that participants can learn a deterministic distractor location sequence and proactively suppress the anticipated distractor location of the upcoming trial (Wang et al., 2021). Learned suppression has also been observed in the nonspatial domain (see Chelazzi et al., 2019; Geng et al., 2019; van Moorselaar & Slagter, 2020; for recent reviews). For example, a given color singleton that initially captures attention does no longer do so when it is experienced repeatedly (Vatterott & Vecera, 2012), and eventually even improves search performance above baseline levels (Cunningham & Egeth, 2016; Gaspelin & Luck, 2018), although the latter effect appears specific to small display sizes in which none of the elements are salient (Wang & Theeuwes, 2020). It has also been shown that distractor colors that appear with a high probability are suppressed more efficiently compared with low probability distractor colors (Stilwell et al., 2019). In addition, feature-based statistical regularities interact with learning in the spatial domain, as reflected by more effective suppression of a distractor presented in the location where its feature (e.g., its color) is more probable (Failing et al., 2019).

Learned suppression is different from voluntary, top-down suppression. Indeed, the improved filtering of distractors with predictable properties (i.e., location or features) is typically an implicit bias, observed without observers expressing either awareness or explicit knowledge of the regularity (e.g., Ferrante et al., 2018; Wang & Theeuwes, 2018; Wang et al., 2021). Wang and Theeuwes (2018) compared distractor suppression driven by statistical learning of the most probably distractor location with explicit cuing of the likely distractor location (on a trial-by-trial basis) and found that explicit cues did not induce a suppression effect. However, whether explicit cues regarding distractor properties can never help to direct attention away from distractor stimuli remains a topic of discussion (see Chelazzi et al., 2019). Cuing the feature of an upcoming distractor (e.g., its color) has, for example, been shown to reduce capture; a finding that has been interpreted as evidence that people can create a template for rejection (Arita et al., 2012). Yet, this interpretation has been challenged (Becker et al., 2016) and more recent data show that the explicit goal of suppressing a given distractor color cannot overwrite the effect of recent experiences (Luck et al., 2021).

Second-Order Suppression

The work discussed above demonstrates the influence of predictable distractor characteristics, such as a recurring distractor location or probable colors of distractors. Recently, however, it has also been proposed that suppression mechanisms do not necessarily selectively operate on specific distractor characteristics but can also achieve "second-order distractor suppression," allowing for the suppression of salient color singleton distractors *independent* of their specific features (Won et al., 2020, 2019). The idea of second-order distractor suppression is based on the finding that probabilistic expectations of color singletons' *occurrence* can eliminate the capture they cause during visual search, despite their location and color being unpredictable (Won et al., 2020, 2019). This suppression effect is indexed by an attenuated distractor response time cost and a reduced number of first saccades to singleton distractors in high-frequency blocks (with 80% of trials containing a distractor), relative to low-frequency blocks (with 20% of trials containing a distractor). A follow-up experiment that used a probe display with a to-be-reported letter inside each shape of the search display further showed that the letter in the distractor location was reported less often in the high- compared with the low-frequency condition (Won et al., 2019). It seems to be the case that, as stated by Won and colleagues (Won et al., 2019), "*having strong expectations for the presence of a [color] singleton enhances suppression mechanisms that are sensitive to second-order salience information*" (pp. 134–135).

Although the findings above indeed suggest that suppression is established on the basis of probabilistic expectations regarding the occurrence of salient distractors, the underlying mechanism is not immediately clear. Expectations given a distractor's location can lead to changes in the weights within the attentional priority map such that the probable location is suppressed relative to all other locations (Wang & Theeuwes, 2018), and expectations regarding the possible colors or shapes of upcoming singletons could in principle be achieved by building internal models for suppression that use either specific features or distributions of features (Chetverikov et al., 2017; Won & Geng, 2018). However, these mechanisms operate on regularities at the first-order level (i.e., regularities regarding the color or location of distractors). What are then the mechanisms that lead to attenuated responses to color singletons in conditions where distractors are very likely but contain no first-order regularities? Whereas this largely remains an open question, a recent functional magnetic resonance imaging (fMRI) study that contrasted high- and low-frequency blocks suggests that second-order singleton suppression is supported by changes in visual cortical processing; within a high-frequency block, the readout of saliency signals (from visual cortex) associated with an expected distractor would be suppressed, resulting in less competition for attentional priority in frontoparietal regions (Won et al., 2020).

Current Study

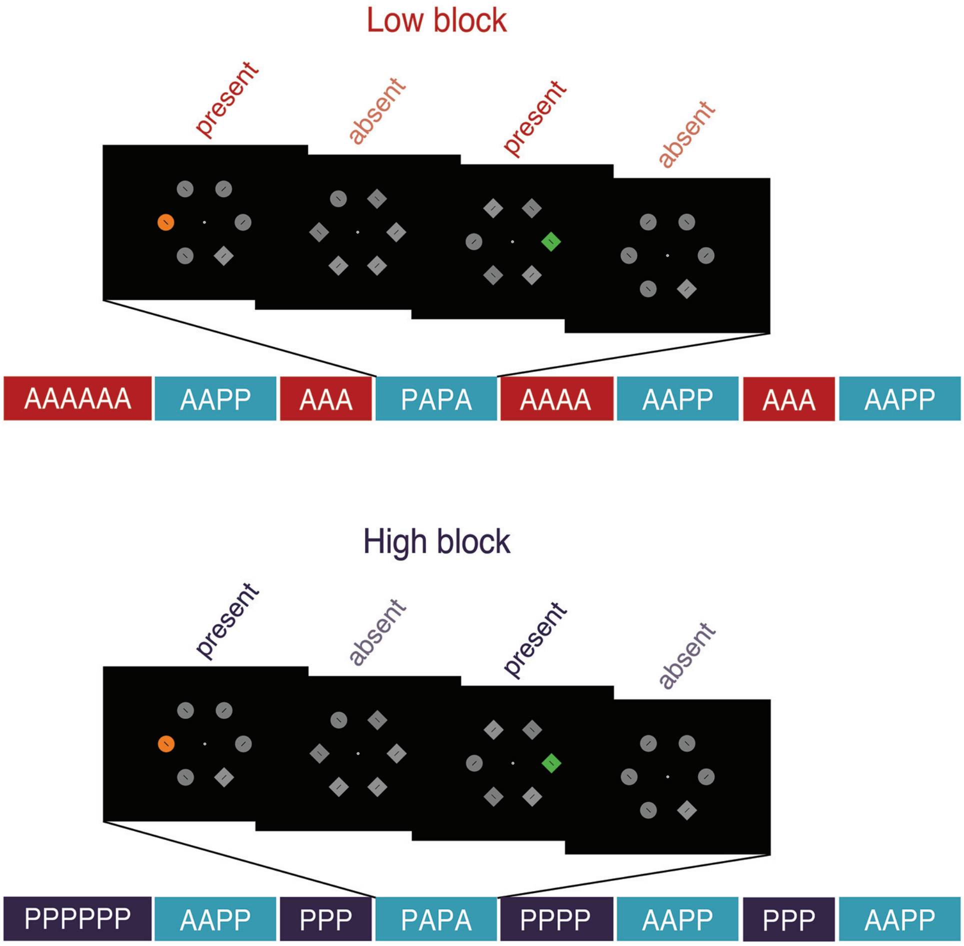
One aspect of second-order distractor suppression that is still unsettled, is the extent to which the phenomenon is intertwined with intertrial repetition priming effects. This is not a trivial issue; indeed, a range of effects in the attentional capture literature that were initially interpreted as condition differences (e.g., increased capture with vs. without target uncertainty, capture by task-contingent cues vs. noncontingent cues) were later shown to be either largely or entirely explainable in terms of intertrial priming (e.g., Belopolsky et al., 2010; Pinto et al., 2005). A frequency manipulation as used by Won and colleagues (Won et al., 2020, 2019) inevitably brings with it an imbalance in the probability of immediate repetitions of certain distractor characteristics (e.g., its features, location). It could thus be argued that the reduced capture in high-frequency blocks could, at least partially, be attributed to intertrial (priming) effects (e.g., Dent, 2018; Geyer et al., 2008). In the studies by Won and colleagues target and distractor shapes randomly swapped across trials, creating optimal conditions for intertrial priming to exert its effects. Before further examining the (neural) mechanisms underlying "second-order distractor suppression" it is critical to establish that the observed effects go above and beyond intertrial repetition effects. Although previous work did demonstrate a lack of significant repetition priming effects for distractor color and distractor location (Won et al., 2019) this does not mean they could not jointly have contributed to faster RTs on distractor present trials and hence a reduced distractor cost.

Aiming to further our understanding of the dynamics of second-order distractor suppression, we examined the effect of learned distractor expectations in highly controlled experimental environments. Instead of generating trials randomly and then omitting all trials on which a (certain type of) repeat occurred to control for intertrial priming effects as is typically done (e.g., Ferrante et al., 2018; Van Moorselaar et al., 2020; Wang & Theeuwes, 2018), we introduce a novel methodological approach (see Figure 1) that allows to contrast search times on identical trial sequences embedded in different experimental conditions. "Identical trial sequences" refers here to the presentation of the very same search displays (i.e., same distractor shape and color, with the distractor presented at the same location), presented in the same order, thus controlling for effects of repetition priming *by design*. First, we examined how probabilistic expectations affect suppression by contrasting search times on trial sequences that were either surrounded by distractor-present filler trials (i.e., *high-frequency condition* with distractors present on 80% of the trials) or by distractor-absent filler trials (i.e., *low-frequency condition* with distractors present on 20% of the trials).

Second, we go beyond the manipulation of distractor frequency and consider a different type of statistical regularity with regard to distractor presence. In the literature on statistical learning it is well established that individuals are sensitive both to distributional information (e.g., the frequency of Y) and to sequential regularities such as the co-occurrences between stimuli in time (e.g., after X always follows Y; Siegelman et al., 2017; Thiessen, 2017; Thiessen

Figure 1

Design of Experiment 1



Note. Every participant completed the two blocks (with block order counterbalanced across participants). Low- and high-frequency blocks contained the exact same present-absent-present-absent (PAPA) and absent-absent-present-present (AAPP) trial sequences, but were surrounded either by only distractor-present filler trials or by only distractor-absent filler trials (3–9 filler trials between each PAPA/AAPP pattern). See the online article for the color version of this figure.

et al., 2012). In Experiment 2, we investigate whether observers also make use of local across-trial regularities regarding distractor presence to better ignore distractors. We hypothesized that giving observers the opportunity to generate (implicit) predictions regarding the absence or presence of a distractor in each upcoming trial would allow them to anticipate distraction and hence also elicit second-order suppression.

Finally, in Experiment 3, we investigate the impact of adding a cue prior to every search display that indicates distractor absence or presence. Here we ask if second-order suppression is under voluntary control in the sense that an explicit expectation regarding distraction in an upcoming search display can enhance suppression mechanisms that are sensitive to second-order salience information.

Experiment 1: Distractor Frequency

Method

Participants

The sample size was determined based on an a-priori power analysis for a paired samples *t* test comparing the size of the attentional capture effect in the two conditions, with a power of 85%, $\alpha = .05$ and Cohen's $d = .4$ (corresponding to an identical value for Cohen's d_z assuming $r = .5$ for the correlation of the repeated measures) as the smallest effect size reflecting a nonnegligible, theoretically meaningful effect in psychological research (see Brysbaert, 2019, for a discussion). This resulted in a sample size of $n = 59$ (calculated using G*Power; Faul et al., 2007).[1] Considering that online studies can yield noisier data as well as larger dropout rates compared to those in the lab, we aimed for a slightly larger sample of 65 individuals. Participants were recruited through the university's online participant recruitment system. One participant was excluded due to low accuracy (<60%), leaving 64 participants (53 females) with a mean age of 20.38 years (range = 18–41). For this experiment as well as subsequent ones, participants received either course credits or payment for their participation. All participants gave their informed consent before beginning the experiment. This study was approved by the Ethical Review Committee of the Faculty of Behavioral and Movement Sciences of Vrije Universiteit Amsterdam.

Apparatus and Materials

The experiment was created in OpenSesame (Mathôt et al., 2012) using the OSweb extension and were run on the JATOS server (Lange et al., 2015). Because the experiment took place online some factors (e.g., screen size, lighting, etc.) could not be controlled. However, all critical comparisons in this experiment and the subsequent ones were *within* subjects.

Search displays in our additional singleton task contained six shapes, either five circles (98px diameter) and one diamonds (118px diagonal), or vice versa. These were arranged on an imaginary circle (radius 224px) around a white central fixation dot (8px radius, 2px hole). Their default color was gray (RGB: 125, 125, 125) and they were all presented on a black background. The target shape could be either a circle (in that case it would be surrounded by five diamonds) or a diamond (surrounded by five circles). Each of the six shapes contained a black line that was tilted 45° to the left or to the right, the orientation being randomly assigned. The target shape appeared equally often in each of the six locations. On distractor-present trials, one of the nontarget shapes was drawn in color, creating a color singleton. Four colors were used: green (86, 176, 48), blue (34, 117, 186), purple (144, 75, 152), and orange (240, 124, 19).

Procedure

The experiment consisted of one low-frequency and one high-frequency block, with the order of the blocks counterbalanced across participants. In one block the same 12 "Present-Absent-Present-Absent" (i.e., PAPA) trial sequences and 12 "Absent-Absent-Present-Present" (i.e., AAPP) trial sequence were presented (see Figure 1). Within these PAPA/AAPP trial sequences the shape, color, and location of distractors (present in half of the trials) was randomly determined for each participant, with the constraint that it appeared equally often as each of the two possible shapes and in each of the four colors. The order in which trial sequences were presented was randomly determined per participant, but then the same order was used for both blocks. In the low-frequency block three to nine distractor-absent filler trials separated trial sequences (making 144 filler trials in total), in the high-frequency block these were Present filler trials. Also, for these Present filler trials the shape, distractors appeared equally often as each of the two possible shapes, in each of the four colors and on each of the locations. Each block contained 240 trials. In the low-frequency block 48 out of 240 trials contained a distractor (20%), in the high-frequency block 192 out of 240 trials contained a distractor (80%). After every block, participants received feedback (average overall RT and average accuracy). As such, block transitions were clearly marked, however, no instructions were given regarding which type of block participants had performed or were about to perform.

Starting the experiment, participants saw two examples of search displays and were explicitly instructed to "try to ignore the colored distractor, as you are looking for the unique target shape." Prior the each experimental block they performed a block of 20 practice trials. These were randomly generated but mirrored the distractor probability of the upcoming low- or high-frequency block. Average performance under 66% or an average response time above 1,500 ms in the practice triggered another practice block (this happened for 13 out of 64 subjects at the first practice, and only for one subject at the second practice).

The trial procedure was identical in all blocks and looked as follows: A fixation dot appeared 500 ms before each search display. Then the search display was presented. Participants had to find the unique shape (either a diamond among circles or a circle among diamonds) and indicate whether the line segment inside this shape was tilted to the left or to the right by pressing the 'left' or 'right' arrow keys on the keyboard as quickly as possible. The search display remained on the screen till a response was given, with a timeout of 2,000 ms. Following a

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[1] Note that previous work by Won et al. (2019) suggests a difference in the capture effect between low- and high frequency conditions with a large effect size of Cohen's $d_z = 1.45$ (for the mixed singleton color in their Experiment 1, calculated based on the publicly available raw data). A power calculation with $n = 64$ and this effect size results in a power of 100%. Given our hypothesis that their effect might have been (partially) driven by intertrial priming we did not base the sample size calculation on this effect size.

correct response, the fixation dot did not change color and was presented for 250 ms. After an incorrect response or in case the participant failed to provide a response within 2,000 ms, the fixation dot turned red (0, 0, 255) for 500 ms. Experiment programs, raw data and analyses scripts are publicly available in the Open Science Framework (OSF) repository: https://osf.io/tyse2/?view_only=c7ab10ca86d94ddb8aa57ec9b730d2c5.

Results

All analyses were performed in R (R Core Team, 2020), with the exception of the SMART method (van Leeuwen et al., 2019) that was implemented in Python. For condition comparisons and tests of intertrial priming we report, in addition to frequentist test statistics, also Bayes Factors (BFs, calculated using the *BayesFactor* package with default priors) that can quantify evidence *against* but also *for* the null hypothesis. BFs reflect the relative likelihood of obtaining the observed data under the null hypothesis compared to the alternative hypothesis (BF_{01}) or vice versa (BF_{10}).

Accuracy

Mean accuracy was 93.14% (*SD* = 5.23%) for the low-frequency block and 92.55% (*SD* = 4.32%) for the high-frequency block.

Reaction Times

Following the methods of Wang and Theeuwes (2018) all trials with incorrect responses as well as trials with RTs faster than 300 ms (deemed too fast to have properly performed the search task, .02% of all trials) were excluded.

For each individual the size of the attentional capture effect (i.e., difference between average RT on distractor present trials and average RT on distractor present trials) was calculated separately for each condition. A paired samples *t* test comparing the size of the attentional capture effect in the high- and low-frequency conditions revealed a larger attentional capture effect in the low-frequency condition, $t(63) = 5.82$, $p < .01$, Cohen's $d_z = .67$, $BF_{10} = 12405.97$ (see Figure 2). Note that for this analysis we included only the trials of the patterns that were presented in both conditions (i.e., excluding the filler trials). To fully control for intertrial priming, the very first trial of a pattern was also excluded. Due to the fact that half of the patterns started with a present trial and the other half with an absent trial this is a balanced comparison. A significant condition difference was further observed for distractor-present trials ($t(63) = 2.82$, $p < .01$, Cohen's $d_z = .35$, $BF_{10} = 5.02$) but not for distractor-absent trials ($t(63) = -.38$, $p = .71$, Cohen's $d_z = .05$, $BF_{01} = 6.82$).[2] The BF for the condition difference for distractor-absent trials indicates that the observed data are about seven times more likely to have occurred under the null hypothesis. The capture effect in both conditions was reliably larger than zero (low-frequency: $t(63) = 12.90$, $p < .001$, Cohen's $d_z = 1.61$; high-frequency: $t(63) = 8.17$, $p < .001$, Cohen's $d_z = 1.02$).

Time-Course of the Condition Effect

After having established that in high-frequency blocks attentional capture is attenuated relative to low frequency blocks, we explored whether this dissociation gradually emerged, or alternatively was established rapidly. Panel A of Figure 3 shows the development of RTs across search trials within the low- and high-frequency blocks. As we focus again on the trials of the patterns that were presented in both conditions (i.e., excluding the filler trials) RTs were analyzed as a function of the order of the pattern within a block. There were 24 patterns in each block, hence the pattern number ranges from 1 (first pattern presented in the block, following 3–9 filler trials) to 24 (last pattern presented in the block). As in the previous analysis, we only included search trials with correct responses and only trials from PAPA/AAPP patterns, however for this analysis we did not exclude the first trial of every pattern. Using the SMART method (van Leeuwen et al., 2019), a moving Gaussian window (step size = 1, $\sigma = 2$) was used to create weighted smoothed time series. We used cluster-based permutation testing (with 1,000 permutations and a significance threshold of $p < .05$) to statistically test for condition differences while controlling for multiple comparisons. A first cluster-based test compared high- and low-frequency conditions for distractor present trials, revealing one significant cluster ($p < .001$; see Figure 3). We observed a condition difference from the beginning of the experiment, which decreased in size over time. A second test compared high- and low-frequency conditions for distractor absent trials, here no significant cluster was found. Note that the alternative approach of comparing capture itself in low- versus high-frequency blocks in a time-resolved manner led to a near-identical result (one significant early cluster including samples ranging from pattern number 1 to 16, with $p < .001$; see Figure 3, panel B).

The results reported for Experiment 1 were replicated in a near-identical experiment that we ran to examine the possibility that the suppression observed with the frequency manipulation is simply due to increased habituation (e.g., Turatto et al., 2018; Won & Geng, 2020) to the set of the distractor features in the high-frequency condition (where the participants observed more distractors). In this control experiment a low- and high-frequency condition were again compared, but the color singleton distractors presented in filler trials were of a different color set than the distractors presented within the pattern trials sequences of interest. The results of this experiment are included in the Appendix (Figure A1).

Discussion

To address the concern that reduced distractor costs in previous investigations could have been caused by intertrial priming effects, Experiment 1 reexamined the second-order distractor suppression effect while strictly controlling for effects of repetition priming. Making use of the classic additional singleton paradigm with color singletons as distractors, this experiment manipulated the frequency of distractor occurrence while controlling for intertrial priming. In our novel experimental design identical four-trial sequences were once surrounded by sequences of present trials (i.e., *high-frequency condition*) and once by absent trials (i.e., *low-frequency condition*). Analyzing only RTs on the last three trials of those identical trial sequences, we fully control for immediate (N-1) repetition priming effects. Whereas we did not observe a total elimination of capture

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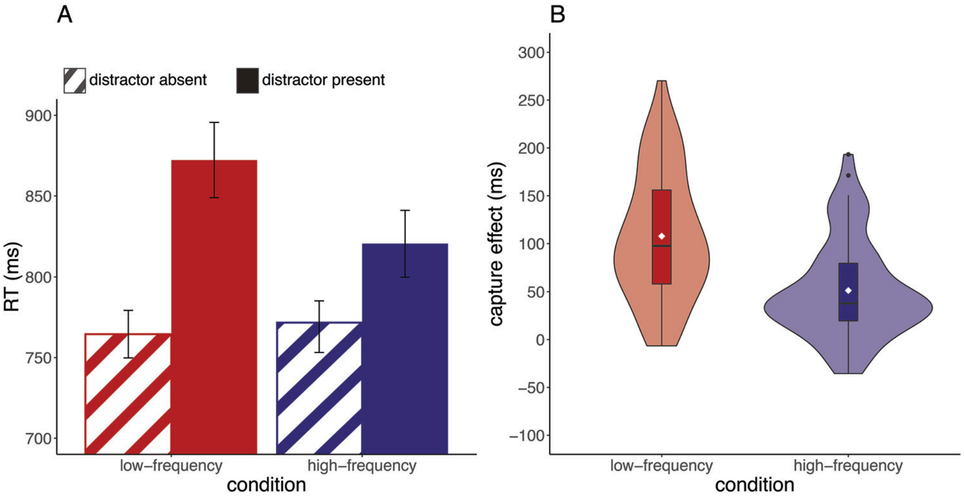
[2] We observed highly comparable RTs for first and second absent trials within the PAPA and AAPP patterns, in both the low frequency (first: $M = 764.12$, $SD = 123.41$; second: $M = 762.86$, $SD = 114.38$; $t(63) = 0.93$, $p = 0.35$, Cohen's $d_z = 0.12$, $BF_{10} = 4.82$) and high frequency (first: $M = 772.94$, $SD = 124.67$; second: $M = 766.18$, $SD = 120.10$; $t(63) = 0.19$, $p = 0.85$, Cohen's $d_z = 0.02$, $BF_{10} = 7.18$) conditions.

Figure 2

Attentional Capture in Experiment 1



Note. (A) RTs in function of distractor presence and condition. Error bars denote 95% within-subject confidence intervals (Morey, 2008). (B) Capture (i.e., difference in RT between distractor present and absent trials) in the two conditions. White diamonds show the means and midlines represent medians. Box limits indicate the 25th and 75th percentiles and whiskers extend to minimum and maximum value, with the exception of outliers (depicted as black dots). The shape around each boxplot reflects the kernel probability density at the different magnitudes. See the online article for the color version of this figure.

in the high-frequency condition as reported previously (Won et al., 2019), we did find significant attenuation of attentional capture. Our findings unequivocally show that a same distractor (e.g., a blue circle) presented in an identical search display (and following on an identical search display), is more distracting when presented in a context with less frequent distractor occurrences. This suggests that the previously reported attenuation of distractors in conditions with a high likelihood of distractor occurrences (compared with conditions with a low likelihood of distractor occurrences) is robust and cannot simply be explained by intertrial repetition priming. In addition, in previous reports on the second-order suppression effect, reduced capture in a high-frequency condition was driven not only by decreased RTs on distractor-present trials—as would be predicted by enhanced distractor suppression—but also by an unexplained increase in RTs (or inversed efficiency scores) for distractor-absent trials in that same condition (Won et al., 2020, 2019). Our results, by contrast, show highly comparable performance on distractor-absent trials and hence a reduction in the distractor cost that is clearly driven by a different response to distractors presence. This strengthens the inference that the observed attenuation of attentional capture is in truth caused by enhanced distractor suppression mechanisms. Other recent evidence supporting the conclusion that distractor frequency per se is a factor that modulates capture comes from the study by Valsecchi and Turatto (2021). This work demonstrated that distractor filtering is affected by both local and global distractor probability; when leaving the frequency of distractor occurrence at a particular location unchanged, increasing the overall distractor frequency in the search task (by increasing the frequency at other locations) leads to less capture at that particular location (Valsecchi & Turatto, 2021).

To the best of our knowledge, no previous work has explored the time-course of second-order suppression elicited by conditions with a high distractor frequency. Our analysis of the time-course of the condition effect revealed, somewhat surprisingly, that the high-frequency condition is characterized by significantly faster RTs on distractor present trials and hence significantly smaller capture already for early patterns occurring at the start of the block. Note that the very early condition difference in capture size is a replicable result, as we observed a comparable time-course in Experiment 1B (see Appendix). This suggests that short exposure to differential distributional statistics is sufficient to induce differential expectations of color singletons' occurrence. If subjects were updating their expectations by weighting all previously encountered trials within the current context and were applying second-order suppression proportionally to expectation strength, one could have predicted a growing difference between the two conditions. Our findings, in contrast, show that it is the earlier search trials in each of the conditions that show the largest differences; over time attentional capture is reduced, also in the low-frequency condition.[3] Based on this result, one could argue that there is initially an overrelaxation of nonspecific suppression mechanisms when distractors are rare, followed by some correction. When confronted with many distractors, on the other hand, nonspecific suppression is rapidly in place. The observed time-course suggests that probabilistic expectations regarding distractor occurrence are formed very rapidly and speaks to the remarkable flexibility of second-order suppression, a

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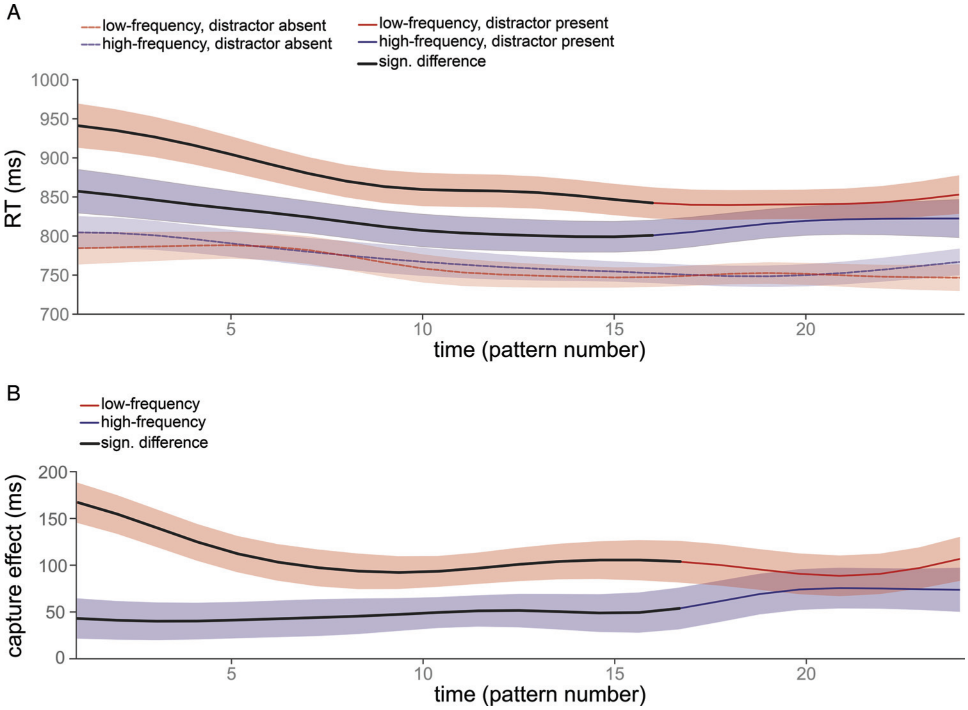
[3] We reasoned that the shrinking of the second-order suppression effect as a block progresses could, in principle, be due to post-error slowing: with more errors at the start of the low-frequency block (relative to the high-frequency block), the larger number of trials following an incorrect response (with long RTs due to post-error slowing) could lead to longer average RTs. We did, however, not find evidence in support of this explanation. An analysis on a subset of the data, excluding all trials following an error, revealed a highly significant condition difference with a comparable time-course.

Figure 3

Time-Course of the Condition Effect in Experiment 1



Note. (A) RTs as a function of distractor presence, condition and time within the block (i.e., pattern number 1 to 24). Cluster tests compared between conditions for either absent or present trials. (B) Capture in the two conditions as a function of time within the block. A cluster test compared capture between the two conditions. Significant clusters are indicated in black. The shaded area around the lines shows the 95% confidence intervals (van Leeuwen et al., 2019). See the online article for the color version of this figure.

flexibility that had so far only been reported for learned suppression based on predictable distractor characteristics (e.g., Valsecchi & Turatto, 2021; Wang & Theeuwes, 2020; Won et al., 2021).

The time-course of second-order suppression with a large condition difference very early on seems at odds with explanations of enhanced distractor suppression in high-frequency conditions solely in terms of habituation (e.g., Turatto & Pascucci, 2016; Won & Geng, 2020). Being a mechanism based on simple exposure, habituation is thought to result from a reduction in the responsivity of neurons that encode recurring sensory properties (Geng et al., 2019), and as such it predicts a steady decline in capture with more exposure to the distractor features. In an additional control experiment that we report in the Appendix, we replicated the time-course of reduced capture in a high-frequency condition (relative to a low-frequency condition) when the amount of exposure for distractor features within patterns is equated between conditions. That said, we do preclude that passive suppression mechanisms such as habituation could occur jointly with the type of active suppression elicited by distributional statistical regularities at play here (see Chelazzi et al., 2019; Geng et al., 2019, for discussions of multiple distractor suppression mechanisms).

As originally proposed by Won et al. (2019), it might be participants' *expectation* of the presence of a singleton distractor in the context of the current block that drives second-order distractor suppression. Moreover, our findings suggest that such expectations that trigger second-order suppression are formed very rapidly. This let us to ask whether other types of statistical regularities that could lead to the formation of (implicit) expectations regarding distraction also elicit second-order distractor suppression. More specifically, we ask if humans are able to adopt a general color singleton suppression mode when color singleton distractors cannot be expected probabilistically given their frequency in a given context, but rather can be expected in the sense that their occurrence is fully predictable within a sequence of trials. If that is the case, then introducing a simple regularity regarding the presence and absence of distractors (i.e., sequential *condition*) should lead to an attenuation of capture in comparison to a condition in which distractor presence is equally frequent but unpredictable (i.e., random *condition*). This prediction was tested in Experiment 2.

Experiment 2: Trial-by-Trial Predictability

Method

Participants

We aimed for a sample size identical to the one of Experiment 1 ($n = 64$). Sixty-four healthy individuals (51 females) with a mean age of 21.19 years (range = 18–52), recruited through the university's online recruitment system, successfully completed this second online experiment.

Apparatus and Materials

Identical to Experiment 1.

Procedure

The experiment consisted of two sequential blocks and two random blocks, with the order of the four blocks fully counterbalanced across participants (see Figure 4). In one sequential block the same "Present-Absent-Present-Absent" (i.e., PAPA) trial sequence was repeated 24 times. In the other sequential block a "Absent-Absent-Present-Present" (i.e., AAPP) trial sequence was repeated 24 times. Each sequential block thus had 96 trials. Repeating a same four-trial sequence over and over again made the presence of a distractor in a search display fully predictable given the local trial sequence. The shape, color and location of distractors (present in half of the trials) were randomly determined for each participant, with the constraint that it appeared equally often as each of the two possible shapes and in each of the four colors. Each shape-color combination and each of the six locations occurred with equal frequency. In the random blocks we presented the exact same PAPA and AAPP trial sequences (intermixing these two types of patterns) that an individual had encountered or would later encounter in the structured block, but we intermixed them with one to three random filler trials (48 filler trials in total, half of which were distractor present trials) such that each sequential block had 144 trials. In contrast to the sequential blocks, this made the presence of a distractor highly unpredictable based on either the previous trial or the previous two trials.[4] After every block, participants received feedback (average overall RT and average accuracy).

Instructions and procedures were identical to those for Experiment 1. As before, no instructions were given regarding which type of block participants had performed or were about to perform. At the start of the experiment participants performed 20 practice trials, which were randomly drawn from the trial sequence generated for both of the random blocks. Average accuracy under 66% or an average response time above 1,500 ms in the practice triggered another practice block (this happened for 11 out of 64 subjects).

Results

Accuracy

Mean accuracy was 91.40% (*SD* = 5.24%) for the random blocks and 92.39% (*SD* = 4.96%) for the sequential blocks.

Reaction Times

As above, all trials with incorrect responses as well as trials with RTs faster than 300 ms (.11% of all trials) were excluded. For each individual their attentional capture effect was calculated separately for each condition. A paired samples *t* test comparing the size of the attentional capture effect in the two conditions revealed no significant effect, $t(63) = .51$, $p = .61$, Cohen's $d_z = .06$ (see Figure 5). The observation that the size of the capture effect is similar in both conditions is supported by a Bayesian paired-samples *t* test with $\mathrm{BF}_{01} = 6.67$, indicating that the data are over six times more likely under the null hypothesis (i.e., no difference in the size of the capture effect) than under the alternative hypothesis of a condition difference. The capture effect in both conditions was reliably larger than 0 (random: $t(63) = 9.59$, $p < .001$, Cohen's $d_z = 1.21$; sequential: $t(63) = 8.76$, $p < .001$, Cohen's $d_z = 1.10$). Note that for this analysis we include only the trials of the patterns that were presented in both conditions (i.e., excluding the filler trials in the random blocks).[5]

This pattern of results holds for both PAPA and AAPP patterns when analyzed separately, with $t(63) = .13$, $p = .90$, Cohen's $d_z = .02$, $\mathrm{BF}_{01} = 7.72$ and $t(63) = .43$, $p = .67$, Cohen's $d_z = .05$, $\mathrm{BF}_{01} = 6.67$, respectively.

Time-Course of the Condition Effect

Could it be that the overall block averages are not the most sensitive measure and a condition difference does gradually emerge (as learning of the sequential structure takes place)? Figure 6 shows the development of RTs across search trials within the random and sequential blocks. As can be seen in the figure, the lack of a condition difference is characteristic for the entire timecourse. Indeed, with the SMART method described above (see Results section of Experiment 1), no clusters were detected.

Comparison Between Experiments

Whereas we observed a significant condition difference in Experiment 1, we did not in Experiment 2. But are the results of the two experiments also statistically different? That is, does the frequency manipulation affect capture significantly more than trial-to-trial predictability? To address this question, we calculated, for each subject, the modulation of their attentional capture Effect × Condition × Taking the difference score between the size of attentional capture in Condition 1 (i.e., low-frequency condition for Experiment 1, random condition for Experiment 2) and the size of attentional capture in Condition 2 (i.e., high-frequency condition for Experiment 1, sequential condition for Experiment 2). We then performed an independent samples *t* test directly comparing the size of the condition effect in the two experiments. The result revealed that attentional capture was indeed affected significantly more by the manipulations of, respectively, distractor frequency compared to distractor predictability, $t(108.93) = 3.89$, $p < .001$, Cohen's $d = .69$, $\mathrm{BF}_{10} = 144.18$.

Discussion

Probabilistic expectations elicited by a distributional statistical regularity regarding distractor presence lead to reduced attentional capture (Won et al., 2019, our Experiment 1), but can observers

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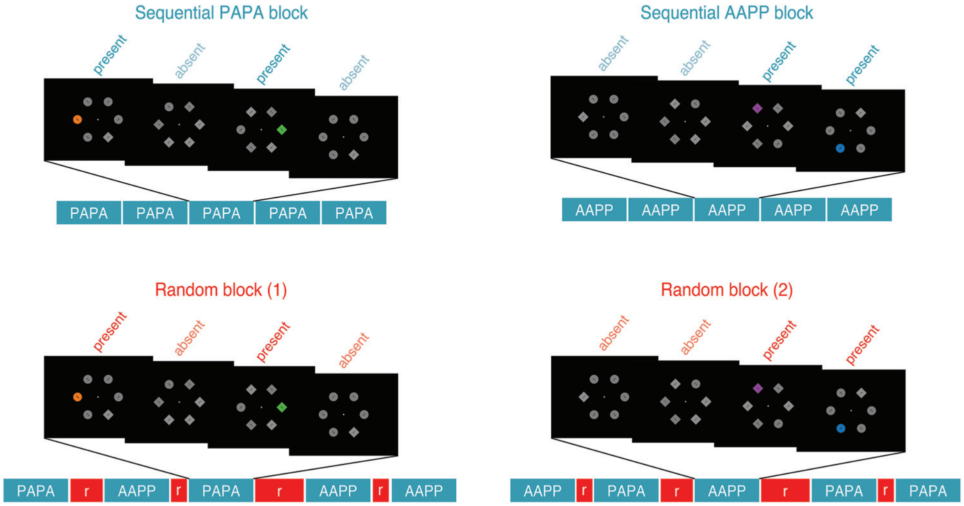
[4] In a structured PAPA block distractor presence on trial N was 100% predictable from trial N-1 (with transitional probabilities $p(A_N|P_{N-1}) = 1$ and $p(P_N|A_{N-1}) = 1$), in a AAPP block distractor presence on trial N was fully predictable from trials N-2 and N-1 ($p(A_N|P_{N-2}\ P_{N-1}) = 1$; $p(A_N|P_{N-2}\ A_{N-1}) = 1$; $p(P_N|A_{N-2}\ A_{N-1}) = 1$; $p(P_N|A_{N-2}\ P_{N-1}) = 1$). In the random blocks these same conditional probabilities were all, on average, $p = 0.50$, reflecting an equal probability for trial N to contain a distractor versus not to contain a distractor.

[5] To fully control for intertrial priming, the first trial of a pattern should also not be included. This is indeed what we did for Experiment 1. As our research question here focuses of the effect of predictability we preferred to include all data of the four-trial sequences, but results are qualitatively identical when running the analysis including only second, third, and fourth trials of patterns.

Figure 4

Design of Experiment 2



Note. Every participant completed all four blocks (with block order counterbalanced across participants). Random blocks contained the exact same PAPA and AAPP trial sequences as the structured blocks, but due to the intermixing the two pattern types and the addition of one to three random filler trials distractor presence or absence was much less predictable. See the online article for the color version of this figure.

also facilitate search by exploiting local across-trial regularities regarding distractor presence? Experiment 2 targeted this question and investigated the effect of the predictability of distractors' occurrence on the size of attentional capture. We compared a condition with a simple regularity regarding the presence and absence of distractors to a condition in which distractor presence was equally frequent but unpredictable on a trial-by-trial basis. We tightly controlled effects of intertrial priming (as for Experiment 1) by testing on identical four-trial sequences, once surrounded by sequences of trials following an identical pattern of distractor presence/absence (e.g., "Present-Absent-Present-Absent" or "Absent-Absent-Present-Present") and once by a random mixture of trials.

Our findings demonstrate that regular, repeating absent/present patterns—making an upcoming distractor predictable on the basis of the previous trials—did not result in a significantly reduced color singleton distractor cost. A Bayesian analysis indicated substantial evidence for the null hypothesis (Jeffreys, 1998). Taken together, the results of Experiments 1 and 2 suggest that second-order distractor suppression is elicited by environments characterized by a high likelihood on distractors but that it is not adopted when distractor presence can, in principle, be anticipated on a trial-by-trial basis.[6] This pattern of results is in contrast to the effect of location-based statistical regularities, which have been observed for distributional regularities regarding the distractor location (Ferrante et al., 2018; Wang & Theeuwes, 2018), trial-to-trial distractor location sequences (Wang et al., 2021) as well as implicit cues informative for the upcoming distractor location (Leber et al., 2016). Therefore, even though trial-by-trial regularities regarding a distractor location can be used to mitigate distractor interference by spatial suppression mechanisms, this is not the case for the suppression mechanisms that operate at the second-order level, in the absence of regularities regarding the location of distractors.

A cautionary note regarding the interpretation of the lack of a condition difference in Experiment 2: Had we observed facilitation of search for sequential blocks with distractor regularities, this would have unequivocally demonstrated that participants both learned the regularities (likely implicitly) and use them to mitigate interference caused by predictable distractors. However, the absence of an effect as observed here can logically be attributed to either participants being unable to learn these very simple sequences, or to an inability to use their (implicit) knowledge of the sequences to reduce capture. Whereas we consider the first possibility unlikely, it is hard to rule out. If one would ask participants to report their predictions regarding distractor presence in upcoming trials, or test their awareness of the regularities post hoc, this would only speak to their explicit knowledge, whereas a large body of recent work shows that regularities for which observers have no explicit knowledge can influence both distractor suppression and target facilitation (e.g., Ferrante et al., 2018; Leber et al., 2016; Li & Theeuwes, 2020; B. Wang & Theeuwes, 2018; L. Wang et al., 2021). We follow

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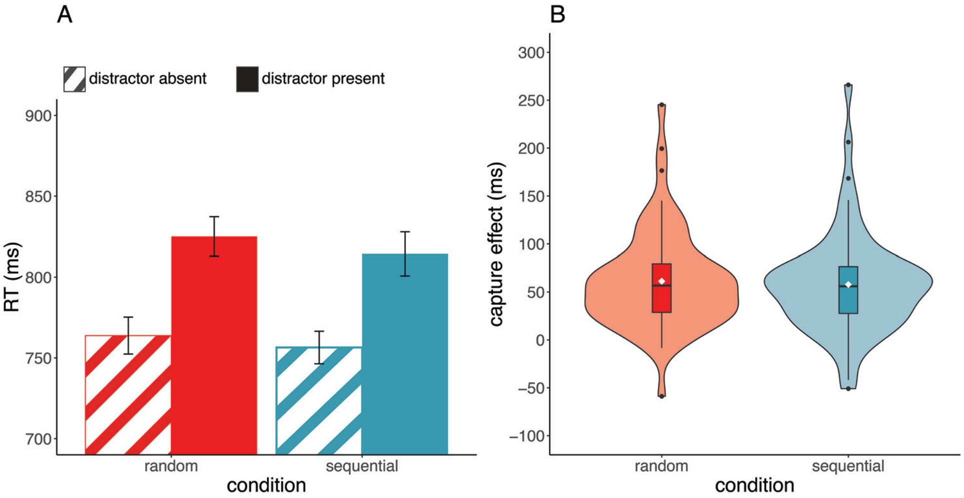
[6] While this was not our main interest, one could also note that the RTs on present trials and the size of capture in both random condition in Experiment 2 (see Figure 6 is comparable the RTs and capture in the high-frequency condition of Experiment 1 (see Figure 2). This suggests that contexts with 50% distractor present trials might, based on probabilistic expectations, elicit as much second-order suppression as contexts with 80% distractor present trials. The questions of what distractor frequency "turns on" second-order suppression, and whether the effect is continuous or rather step-like as our between-experiment comparison might suggest, would be an interesting question for future research. As there still is substantial capture in the random condition of Experiment 2 we argue that local trial predictability could have further reduced capture, yet more research is needed to clarify the potential interactions between the frequency of distractors and the effect of predictable trial sequences.

Figure 5

Attentional Capture in Experiment 2



Note. (A) RTs in function of distractor presence and condition. Error bars denote 95% within-subject confidence intervals. (B) Capture in the two conditions. White diamonds show the means and midlines represent medians. Box limits indicate the 25th and 75th percentiles and whiskers extend to minimum and maximum value, with the exception of outliers (depicted as black dots). The shape around each boxplot reflects the kernel probability density. See the online article for the color version of this figure.

up on this issue with Experiment 3, which induces explicit trial-to-trial expectations.

So far, our experiments induced expectations in an implicit fashion by embedding a statistical regularity in the series of search displays. In the next and final experiment, we further investigate the boundary conditions of second-order suppression. What if distractor presence can be anticipated on a trial-by-trial basis not just given implicitly formed expectations, but also given explicit cues? In Experiment 3, we test the impact of adding an explicit cue regarding distractor presence prior to every search display: we compare a random condition with a repeated uninformative letter cue to a sequential condition with 100% informative letter cues. If explicit trial-by-trial expectations can enhance suppression mechanisms that are sensitive to second-order salience information, we should now observe a condition difference. Alternatively, one could predict that observers cannot make use explicit trial-by-trial expectations to reduce capture.

Experiment 3: Trial-by-Trial Explicit Cues

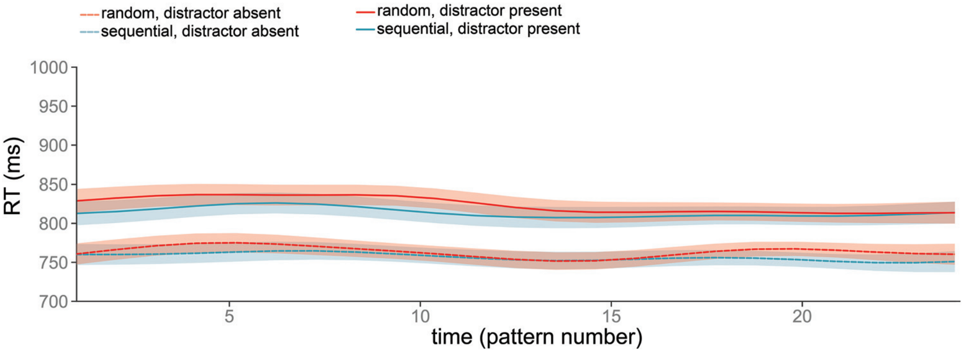
Method

Participants

We aimed for the sample size of Experiment 1 and 2. As data were collected outside of the academic year we could not make use of the university's online recruitment system and we used Prolific (Palan & Schitter, 2018) instead. Sixty-four healthy individuals successfully participated in the online experiment. Three participants were excluded due to low accuracy (<60%), leaving

Figure 6

Time-Course of the Condition Effect in Experiment 2



Note. RTs as a function of distractor presence, condition, and time within the block (i.e., pattern number 1 to 24). The shaded area around the lines shows the 95% confidence intervals. See the online article for the color version of this figure.

61 participants (39 females) with a mean age of 26.03 years (range = 18–35).

Apparatus and Materials

Identical to Experiments 1 and 2. In addition, cues were centrally displayed white letters, in font Mono with font size 40px: X (for every trial in the random block), P (before a distractor present display in the sequential block) and A (before a distractor absent trial in the sequential block). P and A cues were 100% valid, but were only informative about the presence of a color singleton. Cues did not speak to the color, shape, or location of the singleton.

Procedure

Procedures were identical to Experiment 2, except for a modification in the trial procedure adding the explicit letter cue in every trial. At the start of a trial a fixation dot appeared for 250 ms, followed by the cue for 1,000 ms, and again a fixation dot for 250 ms. Hereafter, the search display was presented.

At the start of the experiment participants received explicit instructions regarding the meaning of the letter cues and their informativeness. They saw the following instruction:

> In some blocks, either the letter 'P' or 'A' will be presented before each search display, telling you that either a distractor will be Present ('P') or will be Absent ('A') in the upcoming search display. This information is always valid.
>
> In other blocks, the letter 'X' will be presented before each search display. 'X' means that the search display may or may not have a distractor. It does not provide information.

They subsequently performed 20 practice trials, a miniblock of 10 practice trials contained five A-cues and five P-cues (in random order), another miniblock of 10 trials contained X-cues. Average accuracy under 66% or an average response time above 1,500 ms in the practice triggered another practice of 20 trials (this happened for 25 out of 61 subjects). No instructions were given regarding which type of block (random vs. sequential) participants were about to perform, however, the explicit instructions regarding the meaning of the letter cue(s) in the upcoming block were shown before every block.

Results

Accuracy

Mean accuracy was 91.78% (*SD* = 6.85%) for the random blocks with uninformative cues and 91.78% (*SD* = 6.96%) for the sequential blocks with informative cues.

Reaction Times

As for the previous experiments, we excluded all trials with incorrect responses as well as trials with RTs faster than 300 ms (.26% of all trials). A paired samples t test comparing the size of the attentional capture effect in the two conditions revealed no significant effect, $t(60) = .22$, $p = .83$, Cohen's $d_z = .03$ (see Figure 7). A Bayesian paired-samples t test with $\mathrm{BF}_{01} = 6.98$ indicates that the data are seven times more likely under the null hypothesis than under the alternative hypothesis of a condition difference. In both conditions the capture effect was reliably larger than 0 (random with uninformative cues: $t(60) = 11.30$, $p < .001$, Cohen's $d_z = 1.46$; sequential with informative cues: $t(60) = 12.35$, $p < .001$, Cohen's $d_z = 1.56$). We for these t tests only the trials of the patterns that were presented in both conditions (that is, excluding the filler trials in the random blocks, mimicking the analyses for Experiment 2.[7] This pattern of results holds for both PAPA and AAPP patterns when analyzed separately, with $t(60) = -.55$, $p = .58$, Cohen's $d_z = .07$, $\mathrm{BF}_{01} = 3.96$ and $t(63) = .43$, $t(60) = 1.12$, $p = .27$, Cohen's $d_z = .14$, $\mathrm{BF}_{01} = 3.96$, respectively.

Discussion

In Experiment 3 we manipulated trial-by-trial expectations regarding distractor occurrence *explicitly*. In addition to the simple sequential regularity regarding the presence and absence of distractors, we introduced a letter cue before every search display that indicated whether the upcoming trial would contain a distractor or not (yet it did not speak to its characteristics). This was compared with a random condition in which distractor presence was equally frequent but unpredictable, and which did not contain informative cues.

The results show that even the addition of explicit cues regarding distractor occurrence did not result in a reduced color singleton distractor cost. Therefore, we conclude that second-order suppression is not elicited when the presence of a distractor in an upcoming search display is predictable given the preceding trial sequence, not even when expectations are induced explicitly. The lack of a condition difference (with substantial support for the null hypothesis according to the Bayesian analysis) suggests that nonspecific distractor suppression cannot be accomplished via active, top-down control.

The limited role for active top-down suppression had already been demonstrated for first-order distractor characteristics such as its location (Wang & Theeuwes, 2018) and color (Becker et al., 2016; Gaspelin et al., 2019), but this experiment provides the first investigation of the effect of anticipatory cues on the second-order level. Unlike cuing specific distractor features, which assumes observers can use a template for rejection (Arita et al., 2012; but see Becker et al., 2016), and unlike cuing the likely location of a distractor that could only benefit search if the relative weighting of locations on the spatial priority map is under voluntary control (see Wang & Theeuwes, 2018, for a discussion), the explicit cuing of distractor presence could in principle reduce capture simply by flexibly activating the suppression mechanisms that are sensitive to second-order salience information. The finding that cues do not help to diminish the disrupting effect of color singleton distractors strengthens the interpretation that observers are not able to use their trial-by-trial expectations regarding upcoming distraction—whether implicit or explicit—to reduce capture.

General Discussion

Previous research has demonstrated that in experimental conditions with an increased frequency of singleton distractor occurrences, the attentional capture by distractors—despite their

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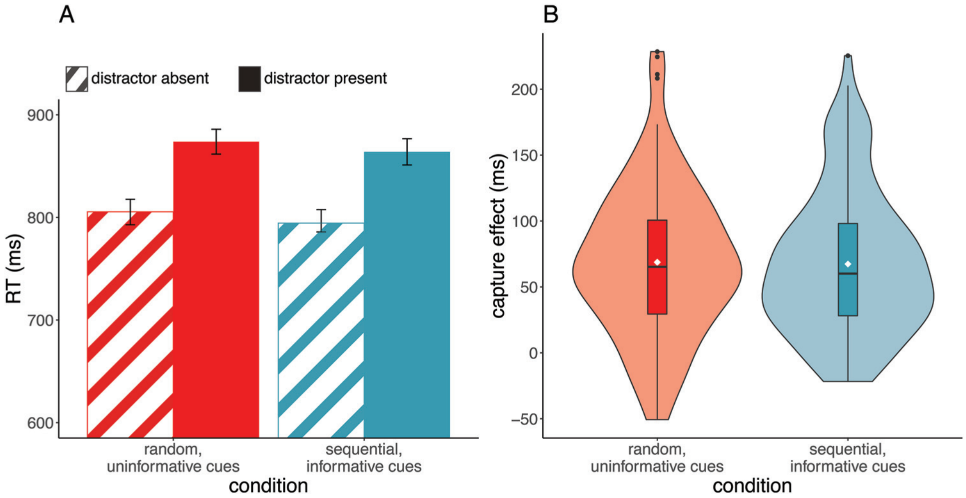
[7] Results are qualitatively identical when running the analysis including only second, third, and fourth trials of patterns.

Figure 7

Attentional Capture in Experiment 3



Note. (A) RTs in function of distractor presence and condition. Error bars denote 95% within-subject confidence intervals. (B) Capture in the two conditions. White diamonds show the means and midlines represent medians. Box limits indicate the 25th and 75th percentiles and whiskers extend to minimum and maximum value, with the exception of outliers (depicted as black dots). The shape around each boxplot reflects the kernel probability density. See the online article for the color version of this figure.

random locations and features—is strongly reduced (Won et al., 2019, 2020). This was taken as evidence that, based on expectations, subjects are able to adopt a nonspecific (hence second-order) singleton suppression mode rather than a specific location- or feature-based suppression mode (Won et al., 2019). Given that this effect had to date only been demonstrated with a frequency manipulation with high-frequency conditions naturally containing a higher probability of immediate repetitions of certain distractor characteristics, a first aim of the current work was to investigate the extent to which the phenomenon is intertwined with intertrial repetition priming effects (see, e.g., Belopolsky et al., 2010; Pinto et al., 2005, for discussions on the large confound that intertrial priming can induce in different experimental manipulations). To this goal, Experiment 1 tested search times on identical trial sequences, embedded in different block contexts. This new experimental approach allowed us to manipulate the frequency of distractor occurrence while controlling for intertrial priming *by design*. Whereas we did not observe a total elimination of capture, we did find significant attenuation of attentional capture in the high-frequency condition, demonstrating that second-order distractor suppression is not merely a result of repetition priming. An investigation of the time-course of this effect shows that enhanced suppression is triggered very swiftly.

Second, we asked if second-order distractor suppression can also be driven by a different type of expectations, namely expectations regarding distractor occurrence within a sequence of trials, formed on the basis of prior experience. To this end, in Experiment 2 we contrasted an experimental condition in which distractor occurrences were either fully predictable or not. Our findings showed that predictable distractor occurrence did not result in a reduced distractor cost and a Bayesian analysis provided substantial evidence in favor of the null hypothesis. This suggests that predictive information regarding the fact that a color singleton distractor is coming up, yet nonspecific in the sense that the location of the upcoming distractor, its shape and color are unpredictable, is not effectively used to shield against distracting information. The juxtaposition of our findings in this experiment manipulating trial-to-trial predictability of distractor occurrence and the findings of our first experiment, which provided evidence for second-order distractor suppression in conditions with a high distractor frequency, suggests that trial-by-trial regularities and distributional regularities (i.e., overall frequency) regarding distractor presence qualitatively differ from one another. It points to an important boundary condition for the ability to apply second-order distractor suppression on the basis of statistical regularities. The distinction between transitional regularities (i.e., learning the co-occurrences of elements in a sequence) and distributional regularities has also been made in the statistical learning literature by accounts that consider this type of learning a *componential* ability that spans several separable dimensions (Growns et al., 2020; Siegelman et al., 2017). Likewise, the emerging literature on learned location-based suppression of distractors induced by spatial statistical regularities suggests that learning is stronger for distributional regularities (e.g., Ferrante et al., 2018; Wang & Theeuwes, 2018) than for spatial regularities that span across trials (e.g., Li et al., 2021). Positing "expectations," broadly defined as the believe that something will or is likely to happen, as the driving mechanism for second-order suppression is, as such, too general. Indeed, this conclusion is further supported by the results of a final cuing experiment (Experiment 3), which showed that establishing explicit expectations regarding distractor presence (on a trial-by-trial basis) did also not result in a reduced color singleton distractor cost. This strengthens the interpretation that observers are able to use probabilistic expectations to reduce capture, but not their trial-by-trial expectations regarding upcoming distraction—whether implicit or explicit. It also suggests that second-order distractor suppression, akin to first-order distractor suppression, cannot be applied under voluntary control.

Finally, from a methodological perspective, the approach to control for intertrial priming introduced in the current article can be a significant asset for future research in the domain of visual attention more generally. Nowadays the common approach for visual search paradigms such as the additional singleton paradigm is to generate search displays randomly. At the analysis stage multiple control analyses are then performed to control for the typically large intertrial priming effects (e.g., Ferrante et al,. 2018; Van Moorselaar et al., 2020; Wang & Theeuwes, 2018). Those control analyses involve omitting all trials on which a (certain type of) target or distractor repeat occurred. Simultaneously controlling for all the different types of intertrial priming, as is done by our novel version of the paradigm, is typically impossible as the omission of a large number of trials inevitably leads to poor statistical power. The flexibility of our approach was already corroborated in the current research through its application in four different experiments, manipulating both the overall frequency and predictability of the occurrence of certain stimuli.

In conclusion, in this article we have introduced a novel experimental approach for manipulating the frequency (Experiment 1 and 1b) and predictability (Experiment 2 and 3) of distractor occurrence while controlling for intertrial priming *by design.* The findings demonstrated that the attenuation of attentional capture through "second-order distractor suppression" (i.e., suppression that is nonspecific to the distractors' characteristics) is a robust phenomenon and not merely a result of repetition priming. However, this nonspecific type of suppression was found to *not* be a response to any type of expectation. Whereas it is promptly elicited by environments characterized by a high likelihood of distractor occurrences, it is not evoked by upcoming distractors that can be anticipated on a trial-by-trial basis. Even when explicit expectations, invoked by letter cues which indicated whether the upcoming search display would contain a distractor or not, did not reduce the disrupting effect of distractors on visual search. This led us to conclude that attentional capture is attenuated by high distractor frequency, but not by trial-by-trial predictability. Together, these findings present a precise further characterization of the recently discovered phenomenon of second-order distractor suppression and an important step toward a better understanding of its underlying cognitive mechanism(s).

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(*Appendix follows*)

Appendix

Additional Control Experiment

Experiment 1b

In Experiment 1B, we investigated the possibility that the suppression observed with the frequency manipulation can be explained by increased habituation to the distractor features (that repeated much more often in the high-frequency block of Experiment 1). In this control experiment a low- and high-frequency condition were again compared, but the "filler trials" in the high-frequency condition contained distractors in different colors. Our results were qualitatively identical to those for Experiment 1.

Method

Participants

Sixty-three healthy individuals (53 females) with a mean age of 20.62 years (range = 18–28), recruited through the university's online recruitment system, successfully completed this online experiment.

Apparatus and Materials

Identical to Experiment 1, except that two sets of four distractor colors were used. A first set included four colors ranging from fuchsia to yellow, 36 °F apart on the color wheel ([242, 0, 218]; [241, 0, 73]; [242, 72, 2]; [242, 218, 3]). A second set included four colors ranging from blue to green, similarly 36 °F apart on the color wheel ([15,24,242]; [0, 169, 242]; [0, 242, 170]; [0, 243, 25]). Note that the closest colors from different conditions differed by 72 °F.

Procedure

Identical to Experiment 1, except that one set of distractor colors was used for pattern trials, and the other set for filler trials. The order of the high versus low blocks and the use of the color sets for pattern versus filler trials was fully counterbalanced between participants (four counterbalancing groups).

Results

Accuracy

Mean accuracy was 92.82% (*SD* = 5.28%) for the low-frequency blocks and 92.28% (*SD* = 4.22%) for the high-frequency block.

Reaction Times

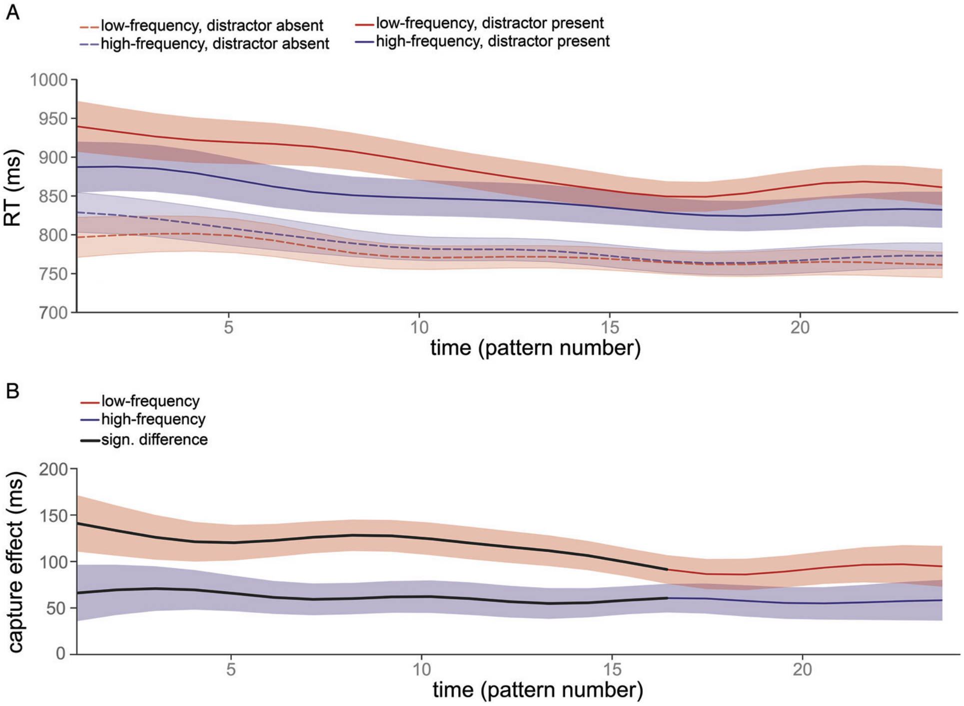
As in Experiment 1, all trials with incorrect responses as well as trials with RTs faster than 300 ms (.03% of all trials) were excluded. As for Experiment 1, for a first set of analyses we excluded filler trials and first trials of pattern sequences. A paired samples *t* test comparing the size of the attentional capture effect in the high- and low-frequency conditions revealed a larger attentional capture effect in the low-frequency condition, $t(62) = 5.03$, $p < .01$, Cohen's $d_z = .63$, $\mathrm{BF}_{10} = 3845.47$. There was a significant condition difference for distractor-present trials ($t(62) = 2.01$, $p = .048$, Cohen's $d_z = .25$, $\mathrm{BF}_{10} = .90$), although note the inconclusive BF. No condition difference was found for distractor-absent trials ($t(62) = -.63$, $p = .53$, Cohen's $d_z = .08$, $\mathrm{BF}_{01} = 5.99$). The capture effect in both conditions was reliably larger than zero (low-frequency: $t(62) = 13.02$, $p < .001$, Cohen's $d_z = 1.63$; high-frequency: $t(63) = 8.37$, $p < .001$, Cohen's $d_z = 1.06$).

Time-Course of the Condition Effect

Panel A of Figure A1 shows the development of RTs across search trials within the low- and high-frequency blocks. RTs were analyzed as a function of the order of the pattern trials within a block. As above, we only included search trials with correct responses and only trials from PAPA/AAPP patterns, however, for this analysis we did not exclude the first trial of every pattern. We used the SMART method (van Leeuwen et al., 2019) with the same parameters as for Experiment 1. Cluster-based tests comparing high- and low-frequency conditions for distractor present trials and for absent trials revealed, respectively, no significant cluster (p = .10) and no cluster. The approach of comparing capture itself in low- versus high-frequency blocks in a time-resolved manner did lead to a significant cluster, replicating the result observed in Experiment 1 (one significant early cluster including samples ranging from pattern number 1 to 16, with $p < .001$, see panel B of Figure A1). As before, it reflects the presence of a condition difference from the start of the experiment, which decreased in size over time.

Figure A1

Time-Course of the Condition Effect in Experiment 1B



Note. (A) RTs as a function of distractor presence, condition and time within the block (i.e., pattern number 1 to 24). (B) Capture in the two conditions as a function of time within the block. A cluster test compared capture between the two conditions. The significant cluster are indicated in black. The shaded area around the lines shows the 95% confidence intervals (van Leeuwen et al., 2019). See the online article for the color version of this figure.

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