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Dynamic suppression of likely distractor locations: Task-critical modulation

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ABSTRACT

When a distractor frequently appears in a certain region of a search display, it interferes less with performance, reflecting learned distractor suppression. While this effect is well established, it remains unknown whether this suppression is ongoing (tonic) or deactivated upon task completion (phasic). To address this, the present eye-tracking study examined the time course of distractor suppression. Participants searched for and compared two targets to determine whether to make a response or withhold responding ("No-go" trials). The No-go trials allowed observation of post-decision suppression via eye movements. Response-critical target features either remained present for the whole trial (Experiment 1) or were removed halfway through (Experiment 2). In Experiment 1, distractors in the frequent region were substantially less likely to attract eye movements, including after inspection of both targets. However, in Experiment 2, the post-target distractor-region effect disappeared when the response-critical information was removed, indicating that suppression operates phasically and flexibly.

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In our daily routines, irrelevant but salient stimuli can disrupt our focus on the task at hand. For instance, pop-up notifications on the computer monitor may interrupt the flow of our writing. However, if we frequently receive such notifications in, say, the upper right corner of the screen, we may become accustomed to the pop-up stimuli and they generate less interference. The question of how to handle salient distractors dynamically through selective attention remains a topic of debate. One paradigm to study how we handle salient distractors based on their spatial occurrence is the distractor-location probability-cueing paradigm (e.g., Goschy et al., 2014; Sauter et al., 2018; Wang & Theeuwes, 2018). Typically in this paradigm, participants search for a salient target in displays that may contain a more salient but task-irrelevant distractor, where the distractor appears more often at one location, or in a region encompassing several locations, compared to others. Studies indicate that when the distractor appears frequently at a specific location, it causes less interference compared to distractors at other, rare locations (Allenmark et al., 2019, 2022; Ferrante et al., 2018; Sauter et al., 2018; Wang & Theeuwes, 2018; Zhang et al., 2019). Interestingly, even though observers may not be consciously aware of the bias in the spatial distractor distribution (e.g., Di Caro et al., 2019; Liesefeld & Müller, 2021; Sauter et al., 2021), they can still implicitly learn it to suppress the frequent distractor location, minimizing distractor interference and thus optimizing search performance.

More recent studies from our lab (Allenmark et al., 2019; Liesefeld & Müller, 2021; Sauter et al., 2018; Zhang et al., 2021) have provided evidence that learning to suppress distractors at frequent locations is modulated by how distractors are defined relative to the target. For example, consider a search scenario where a salient colour-defined distractor is present during a search for a target defined by orientation. In such cases, suppression may affect only local feature-contrast signals generated in the colour dimension. The weight of these colour signals is reduced prior to their integration with signals from other dimensions (e.g., orientation) in the supra-dimensional "attentional-priority" map, a representation assumed to determine which (stimulus)

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location attention is allocated to next (Koch and Ullman 1987). Consequently, the down-weighting of colour signals in the distractor dimension would not impact the selection priority attained by orientation-defined stimuli in the target dimension, which would therefore be the first item(s) to summon focal attention. Conversely, when the distractor and the target are defined in the same dimension, such as when both are defined by orientation, signal down-modulation would strategically have to be implemented at the level of the priority map (if implemented at the level of the orientation dimension, the down-modulation would filter out not only task-irrelevant distractor signals, but also the relevant target signals). Since the locations at which distractors occur frequently are down-modulated on the priority map as a result of statistical learning, this would impact not only the ability of the distractor to summon attention (producing a distractor-location effect), but also that of the the target (giving rise to a target location effect) 2021; (see e.g., Liesefeld & Müller, 2021; Sauter et al., 2018; Zhang et al., 2021). In this interpretation, distractor-location probability cueing is attributed to the "proactive suppression" of locations where distractors have been learned to occur frequently, reducing the power of salient distractors at these locations to capture attention in the first place. (Reactive suppression, by contrast, is the "rejection" of distractors that did capture attention, reducing their priority signal to permit attention to be disengaged and re-allocated to the item with the next highest priority.)

Recent eye-tracking studies have provided some evidence of proactive distractor suppression as defined above, showing that distractors appearing at a frequent distractor location (or a region of frequent locations) are less likely to capture overt attention (measured by saccades) and to hold the eye for a shorter period of time if such a distractor happened to attract the eye (Allenmark et al., 2021; Sauter et al., 2021; Wang et al., 2019). However, these studies have focused on (oculomotor) capture of the first saccade following the display onset, without investigating how long it remains effective over the course of a trial. In other words, it remains unknown whether proactive suppression of likely distractor locations is a *phasic* process, perhaps ramping up already in anticipation of (Wang et al., 2019) or upon the onset of the search display (e.g., Qiu et al., 2023; van Moorselaar et al., 2021) but then petering out after a response decision is made; or, alternatively, whether it is a *tonic* process, operating consistently throughout a trial and potentially even in the inter-trial interval (the latter, e.g., because the down-modulation of frequent distractor locations involves local changes "hardwired" into the system of priority computation; cf. Zhang et al., 2021).

The present study was designed to decide between these alternatives by tracking the time course of distractor suppression over an extended period of time – in a novel "dual-target" search paradigm which, in one condition, left the trial display available to be looked at "passively" after having extracted the task-critical target information and having made a response decision. In more detail, we adapted the dual-target paradigm of Stanković et al. (2024), and the distractor-region probability-cueing paradigm of Sauter et al. (2021) – in particular, the condition in which the distractor was defined in the same dimension as the target – by introducing (i) dual targets that had to be inspected sequentially to make a response decision (which typically took around 1 s); and we introduced (ii) a "Go" vs. "No-go" task design, where, on No-go trials, the display was left in view until a display exposure of 3 secs was reached (i.e., for some 2 secs after the response decision). In Experiment 1, participants had to compare two targets (12°-tilted bars amongst homogeneous vertical background bars). If the response-critical feature of the two targets – the "i" dots at the top or bottom of the target bar – were congruent, they had to make a speeded 2AFC response indicating the positions (top vs. bottom) of these features (Go trials). If they were incongruent, they had to refrain from making a response (No-go trials). As in Sauter et al. (2021), an odd-one-out distractor that was more salient than the two targets could appear in either a frequent distractor region of the display or in a rare region, and we tracked participants eye movements for the whole period of the trial – up to 3,000 ms on No-go trials.

The rationale was that examining for Distractor-Region effects in the late, post-task-decision period of the trial would shed light on whether learned location-based distraction suppression operates phasically or tonically. Assuming that location-based suppression manifests in this late period as well as early on – that is, prior to inspecting the first target or in-between inspecting the first and the second target –, this would argue in favour of tonic distractor suppression. Of course, reactive suppression may also play a role in this, as a distractor that captures the eye early on may be inhibited to prevent the eye from returning to it and so prioritizing selection of the task-relevant target items. If a distractor-region effect was manifest in the late period even after the distractor had captured the eye and had to be rejected, this would provide further evidence in favour of tonic distractor suppression.

In contrast, if the primary function of distractor suppression is to aid in target search, rather than simply suppressing the distractor, then actively continuing to suppress after a decision is made or when response-relevant features are absent may not be the most efficient use of attentional resources. In such cases, phasic suppression that flexibly switches off at the post-decision stage would be more advantageous; that is, we should see little evidence of location-based distractor suppression after the response is made, particularly in the period from around 1–3 s on No-go trials. To validate this hypothesis, in Experiment 2, we removed the response-critical feature (the gap on i-shaped items) half-way through each trial. This was done by filling in the gaps in the i-shaped items, effectively removing the "dots" on which response decisions were based, without making any other changes to the search display[1] (see Figure 1). The goal was to remove the information needed to keep performing the task and decide on a response during the later half of a trial, while keeping changes to the search display minimal.

Experiment 1

Method

Participants

A total of 15 (8 male, 7 female) valid participants (*Mean age* = 28.3, *SD* = 3.2 years) were included in the experiment. All participants self-reported being healthy and had either normal or corrected-to-normal vision. The sample size was determined based on previous studies with similar search displays (Sauter et al., 2019, 2021), which had a large effect size for the distractor-region effect ($d_z = 2.28$ in Sauter et al., 2021; $d_z = 1.01$ in Sauter et al., 2019). A power analysis using G*Power (Faul et al., 2007), with a d_z of 1.01, an alpha level of .05, and power (1-ß) = 0.95, yielded a recommendation of 15 participants. Participants signed informed consent prior to the experiment and received 9 Euros per hour or student credits for their service. The study was approved by the Ethics Board of the LMU Faculty of Psychology and Educational Sciences.

Apparatus and stimuli

Search displays were shown on a 21-inch SONY GDM-F500R CRT screen with a refresh rate of 120 Hz and a resolution of 1024 × 768 pixels. Eye-movements were recorded using an SR Research EyeLink 1000 Desktop Mount eye-tracker, capturing gaze-position data at a sampling rate of 1k Hz. Saccades were identified using the default setting of the eye-tracking system: velocity threshold of 35°/s and acceleration threshold of 9500°/s2. Stimulus presentation and response collection were controlled by customized scripts using PsychoPy3 (Peirce, 2008; Peirce et al., 2019).

The search display and task used in the experiment are illustrated in Figure 1. Essentially, the display and task adapted the paradigm used by Sauter et al., (see their Figure 1A, 2021) in their eye-tracking study to a dual-target search scenario. That is, there were always dual targets (rather than just one) in a search display that consisted of 37 vertical bars, two of which were tilted by 12° or – 12° from the vertical: the two target bars. In half the trials, one of the nontarget (vertical) bars was replaced by a horizontal bar, the distractor. All stimuli were presented in gray (RGB: 127, 127, 127, CIE[Yxy]: 50, .31, .31) against a black background (0.14 cd/m² luminance). The search items were arranged around three (imaginary) concentric circles, with radii of 3°, 6°, and 9°, respectively. The targets and distractor were always presented on the *intermediate* circle, at the 10, 11, 12, 1, 2 o'clock positions on the top semi-circle, and the 4, 5, 6, 7, 8 o'clock positions on the bottom semi-circle (excepting the horizontal 3 and 9 o'clock positions). Thus, out of the total of 37 locations, only 10 were used for target and distractor presentation. Note that the bars (2.025° of visual angle in total length, 0.375° in width) had a small gap (0.188° in size, 0.375°) toward one end, making it look like a dotted "i". While the position of the "i" dot (top or bottom of the bar) was generally randomly determined, it was experimentally controlled for the two target bars. In

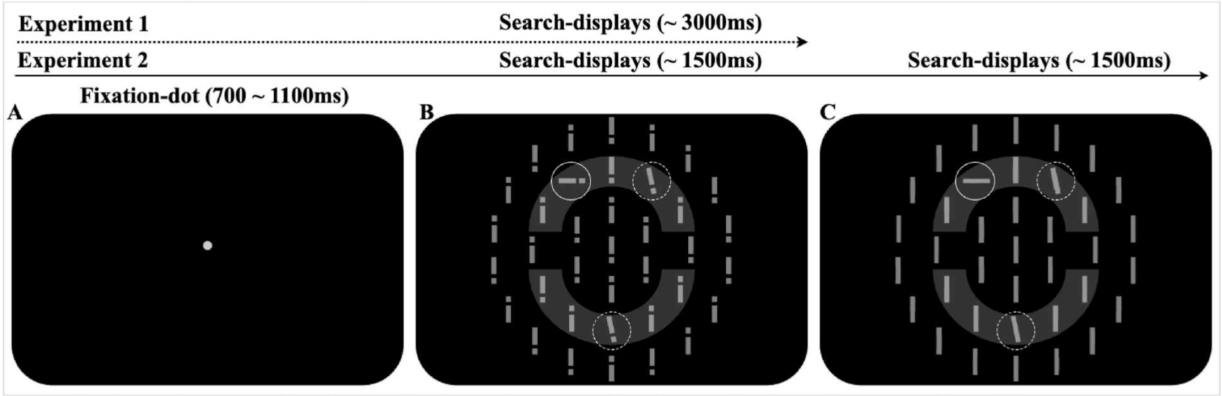

Figure 1. Illustration of display events on a trial. In Experiment 1 each trial began with a central fixation dot presented for 700–1100 ms (panel A), followed by a visual search display (panel B). We adapted the original Sauter et al. (2021) display by implementing a dual-target task. Participants had to fixate the central dot and then, upon exposure to the search display, move their eyes towards the two targets – two slightly left – and/or right-tilted bars in any order. They were required to identify the positions of the "i" dots on the two target bars. If both "i" dots were positioned at the top or both at the bottom, participants had to issue a speeded 2AFC "top" vs. "bottom" response (a "Go" trial; see the right panel for an illustration). However, if one target "i" dot was at the top and the other at the bottom, they were to desist from making a response (i.e., a "No-go" trial). Search-display presentation was terminated after 3000 ms the latest or upon the participants' response. The gray ellipses show the top and bottom semi-circles used as the frequent and, respectively, the rare distractor region. The white dotted circles indicate the two target bars, and the solid circle the distractor (horizontal bar). The coloured ellipses and dotted lines are shown here for illustration purposes only. In Experiment 2, each trial began with a central fixation dot presented for 700–1100 ms (panel A), followed by the visual search display of (panel B) terminated after 1500 ms the latest or upon the participants' response. Then, a masked display was presented (panel C) for 1500 ms, in which all non-targets, distractors, and targets became "I" shapes (i.e, bars with the gaps closed). Search-display presentation was terminated after 1500 ms the latest or upon the participants' response.

80% of the trials, the positions of the "i" dots were the same (both top or both bottom) on the two target bars, while in the remaining 20% of the trials they were different (one top, the other bottom). Presentation of the search array was preceded by a display with a fixation dot (gray, 0.2° in radius) in the centre. Participants were instructed to avoid eye-blinks while the trial display was in view (i.e., for a maximum 3 s, i.e., a short enough period to comply with the instruction on most trials).

Participants were randomly assigned a region in either the top or bottom "half" of the display, in which the distractor appeared with a high probability (90%) on distractor-present trials (accordingly, the probability of a distractor occurring in the other region was 10%). Seven observers were assigned to the bottom half of the display, while eight observers were assigned to the top half. The two targets had an equal chance of appearing at any of the 10 (used) locations on the intermediate ring, but never at directly adjacent locations and (on distractor-present trials) never at the distractor location. The experiment consisted of 1,008 trials, divided into 24 blocks with 42 trials in each block. Participants could make a break after completing each block of trials.

Procedure

The experiment was conducted in a sound-attenuated dark laboratory cabin. The participants were seated comfortably, 60 cm away from the presentation monitor, with head position and viewing distance maintained by the use of a chin-rest. As shown in Figure 1, each presentation started with a fixation dot in the centre of the screen, which lasted randomly between 700 and 1100 ms. During the fixation phase, if participants failed to focus their gaze on the fixation dot, a warning message reading "Please fixate the dot in the center" would appear on the monitor for 1000 ms, and the fixation display started again. After the fixation display, a search display was shown for a maximum of 3000 ms, or until participants terminated the trial by issuing a button-press response. A 500-ms blank interval then led to the next trial.

Participants' were instructed to find, by moving their eyes to, the two oblique target bars, while ignoring any (more salient) horizontal distractor bar in the display. Further, participants were required to discern the position of the "i" dot on each target bar. If the "i" dots on the two targets were both positioned at the top or both at the bottom of the bars (i.e., "Go trials"), they had to report the top vs. bottom positions by pressing either the "J" or the "F" key on the keyboard. However, if one target had a dot at the top and the other a dot at the bottom position, they were to withhold a response (i.e., "No-go trials"). Participants were told to perform this task as fast and accurately as possible. We recorded response accuracy and reaction time (RT) for trials that required a response (Go trials), and (only) accuracy for the other (No-go) trials. The latter made up 20% of all trials. Moreover, we discouraged participants from blinking while searching and recorded their eye movements.

To test whether participants had gained any explicit knowledge of the statistical bias in the spatial distribution of the distractor (which appeared either frequently in the lower display half an rarely in the upper half, or vice versa), participants were asked after they had completed the search task whether the distractors had appeared more often in certain display regions, that is: they had to make a four-forced-choice decision indicating whether distractors had appeared more often in the "right," "bottom," or "left", or "top". Only 4 out of the 15 participants picked the correct response, providing little evidence that participants had become explicitly aware of the bias in the distractor distribution.

Data analyses

The accuracies were calculated separately per Response type: Go vs. No-Go, and Distractor condition: distractor absent vs. distractor (at a location) in the frequent region vs. distractor (at a location) in the rare region. As for the analysis of mean reaction times (RTs), we excluded trials on which the RT was less than 150 ms ("fast-guess" responses). Further, we conducted a within-participant ANOVA, followed by post-hoc pairwise t-tests if necessary. For each analysis based on an ANOVA with a factor with more than two levels, we checked for sphericity violations using Mauchly's sphericity test. If a violation occurred, we applied Greenhouse-Geisser corrections to the degrees of freedom. Moreover, we checked for violations of the homogeneity of variance using Levene's test for between-group comparisons, which yielded no significant violation. In addition, we report effect sizes (η_p^2 or Cohen's *d*s).

Furthermore, we classified saccades based on the default setting of the eye-tracking system: velocity threshold of 35°/s and acceleration threshold of 9500°/s^2. We classified fixations as having landed on a target or the distractor if its first landing position was within 3° of the respective item (if it was within 3° of both a target and the distractor, it was classified as having landed on the item that was closer to the endpoint of the saccade).

Results

Behavioural results

Overall, observers' performance accuracy was relatively high (mean: 95%, range: 77% – 100%), without a difference between Go (95.8%) and No-Go (93.9%) trials, $t(14) = 1.67$, $p = .117$, $d = 0.43$. The mean RT for correct Go-trials was 1185 ms (range: 639–1849 ms).

A repeated-measures ANOVA of the go-trial mean RTs with the single factor Distractor condition (distractor absent, in frequent region, in rare region) revealed the main effect to be significant, $F(1.48, 14) = 67.15$, $p < .001$, $\eta_p^2 = 0.83$. We applied the Greenhouse-Geisser-corrected degrees of freedom. Participants responded fastest when the distractor was absent (1076 ms) compared to both when it appeared in the frequent distractor region (1182 ms) (Figure 2A), Bonferroni-corrected $t(14) = -7.04$, $p < .001$, $d = 1.82$; and when it appeared in the rare region (1297 ms); $t(14) = 9.15$, $p < .001$, $d = 2.36$. Critically, responses were faster when the singleton distractor appeared in the frequent vs. the rare region, $t(14) = -6.85$, $p < .001$, $d = 1.77$, replicating the "standard" distractor-location probability-cueing effect.[2] Furthermore, we confirmed that the distractor-location effect was present regardless of whether the frequent distractor region was in the upper part of the display (108 ms, $t(7) = 4.22$, $p = .004$) or the lower part (127 ms, $t(6) = 6.21$, $p < .001$).

There were no differences in the mean accuracies among the three distractor conditions, $F(2, 28) = 0.71$, $p = .499$, $\eta_p^2 = 0.05$: 95.4%, 95%, and 94.1% for the distractor-absent, distractor-in-frequent-, and distractor-in-rare-region conditions, respectively (Figure 2B). Thus, the RT effects are not compromised by speed-accuracy trade-offs.

Suppression of the frequent distractor region can also impact processing of the target when it occurs in that region, resulting in a target-location effect: slower RTs when the target appears in the frequent

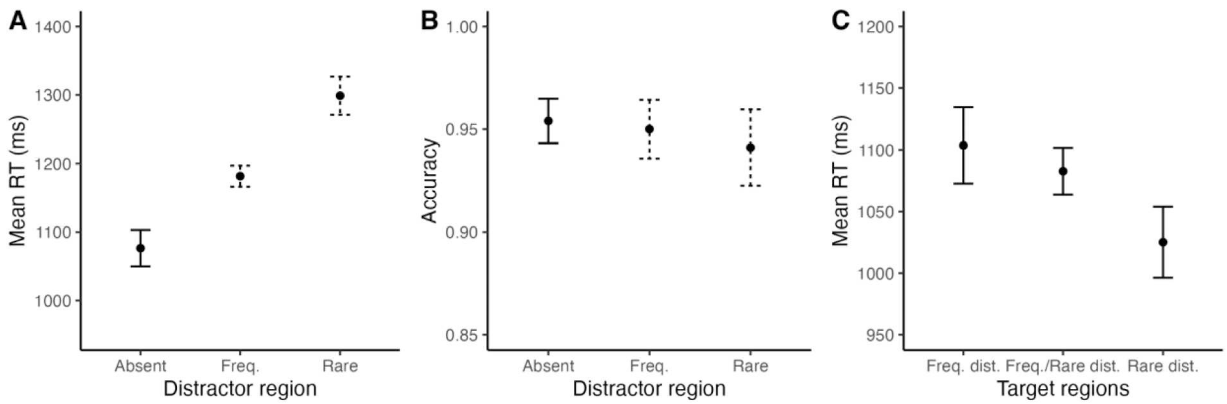

Figure 2. Mean "go"-trial RTs in milliseconds (**A**) and mean response accuracies in percent (**B**) for the three Distractor conditions (distractor absent, distractor in frequent region, distractor in rare region). (**C**) Mean go-trial RTs on distractor-absent trials as a function of the region(s) in which the two targets were located: both in the frequent distractor region (Freq. dist.), one in the frequent and one in the rare distractor region (Freq./Rare dist.), both in the rare distractor region (Rare dist.). Error bars indicate within-subject 95% confidence intervals (Cousineau, 2005).

compared to the rare distractor region (see e.g., Sauter et al., 2018; Zhang et al., 2019), most prominently seen if the distractor is defined in the same dimension as the target (see e.g., Sauter et al., 2018; Zhang et al., 2019). To test for such a target-location effect in the present study, we analyzed RTs on distractor-absent trials as a function of the distractor region(s) in which the two targets appeared: both in the frequent region, both in the rare distractor region, or one in the frequent and one in the rare region.[3] The results are depicted in Figure 2C. A repeated-measures ANOVA with the single factor Target Region revealed the main effect to be significant, $F(2, 28) = 7.58$, $p < 0.01$, $\eta_p^2 = 0.35$: RTs were significantly slower when both targets appeared in the frequent region compared to when both occurred in the rare region (1104 ms vs. 1025 ms; Bonferroni-corrected $t(14) = 3.76$, $p < .01$); they were also slower when one target appeared in the frequent and one in the rare region compared to when both occurred in the rare region (1083 ms vs. 1025 ms; $t(14) = 2.76$, $p < .05$). There was also a small difference between "both targets in the frequent region" (1104 ms) and "one in the frequent, the other in the rare region" (1083 ms), which was however not significant, $t(14) = 1.11$, $p = .83$. Thus, there was a robust target-location effect, in addition to the distractor-location effect.

Eye-tracking results

First fixations. Most of the initial fixations were on one of the salient items, one of the targets or the distractor (with initial fixations on some "other" item being relatively rare). On distractor-absent trials, 81% of the first saccades were directed to a target. Target-directed first saccades were reduced to 60% on distractor-present trials, with the distractor attracting 24% of the first saccades.

To examine for Distractor-Region effects, we divided the initial fixations on distractor-present trials into three categories (to the distractor, a target, and other), separately for the two conditions with the distractor occurring in the frequent and, respectively, the rare region and separately for Go – and No-go trials. See Figure 3 for the results. As can be seen, the proportion of initial fixations on the distractor (depicted in black) was substantially increased, largely at the expense of first fixations on a target (rather than on one of the "other" items), when the distractor appeared in the rare region compared to when it appeared in the frequent region.

A two-way repeated-measures ANOVA on the first fixation to the distractor, with the factors Distractor Region (Frequent vs. Rare) and Response Type (Go vs. No-go), revealed the main effect of Distractor Region to be significant, $F(1,14) = 11.2$, $p < .01$, $\eta_p^2 = 0.44$. There was no effect involving Response Type (main effect: $F(1,14) = 0.004$, $p = .95$, $\eta_p^2 = 0.0003$; interaction: $F(1,14) = 3.3$, $p = .09$, $\eta_p^2 = 0.19$). Thus, when the distractor appeared in the frequent, as opposed to the rare, region, participants' initial saccade was less often directed toward the distractor and, instead, more frequently toward a target. The latter was further confirmed by an analogous ANOVA on the first fixations on the target, which revealed only a

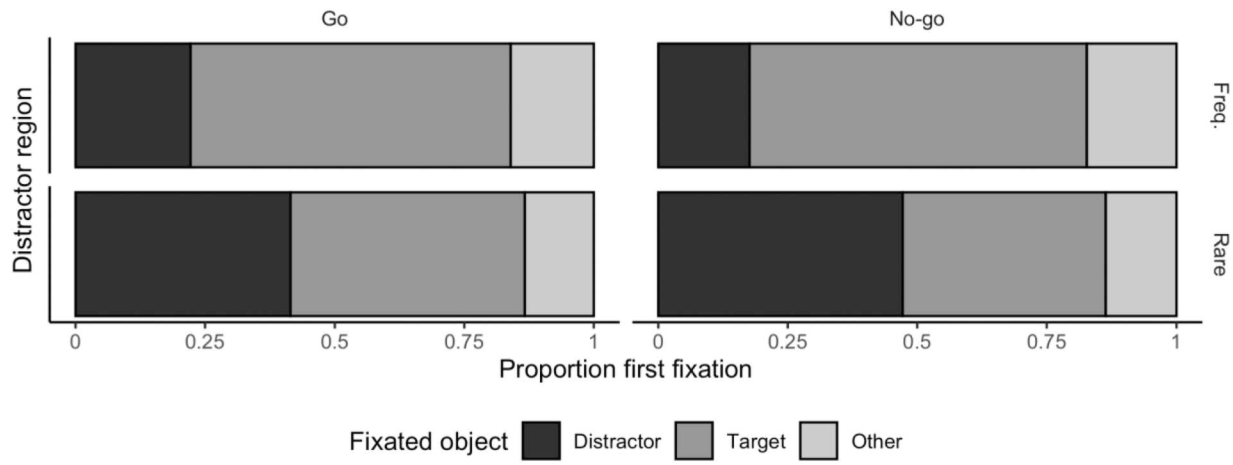

Figure 3. Proportions of first fixations on the distractor, the target, or "another" item on trials with a distractor in the frequent region (upper panels) or the rare region (lower panels), separately for Go trials (left panels) and No-Go trials (right panels).

significant main effect of distractor region, $F(1,14) = 7.1$, $p < .05$, $\eta_p^2 = .34$ (Response Type, $F(1,14) = 0.12$, $p = .74$, $\eta_p^2 < 0.01$; interaction, $F(1,14) = 3.5$, $p = .08$, $\eta_p^2 = 0.20$). Thus, compared to frequent-region distractors, distractors in the rare region gave rise to a significant increase in oculomotor capture and attendant delays in processing the first target. As the initial fixation did not provide sufficient information to decide whether or not to respond (this decision required inspection of both targets to extract the decision-critical features), the lack of a (significant) effect of Response-Type was expected.[4]

Fixations on targets. To determine the patterns of saccades to the targets over the course of the trial, we categorized trials into four target-fixation patterns: (1) "no-fixation" pattern if neither target was fixated before the response (Go trials) or time-out (No-go trials); (2) "single-target-fixation" pattern if only one target was fixated prior to response or timeout; (3) "both-target-fixation" pattern if both targets were fixated without returning to the first target; and (4) "target re-fixation" pattern if the first target was fixated again after the second target.

Figure 4 shows how the distribution of target-fixation patterns varied between Go and No-go trials. In Go trials, the most prevalent pattern was to fixate on both targets without revisiting the first target (observed in 42% of trials). The second – and third-most frequent patterns were "re-fixation" (27%) and "single fixation" (24%). Since accuracy was overall high, including on No-go trials, we believe most of the "single-fixation" pattern trials reflect trials in which participants did process both targets, but processed one of them in peripheral vision while fixating a nearby item. On No-go trials, by contrast, there was a greatly increased (in fact, more than doubled) proportion of "re-fixation" patterns (64%), at the expense of single-fixation and both-fixation patterns – likely because participants used the extra presentation time (up to 3 s) on such trials to check that it was indeed a response-inhibition trial (i.e., that the "i" dots in the two targets were incongruently positioned).

We further examined whether statistically learned suppression of the frequent region would extend to targets appearing there in terms of first fixations. We analyzed first saccades toward the target on distractor-absent trials, considering the Response Type (Go vs. No-go) and the Region(s) where the targets appeared (both in the frequent region, one in the frequent/the other in the rare region, both in the rare region). Numerically, a smaller proportion of the first saccades landed on a target when both targets were in the frequent region (76%), compared to when one (81%) or both of them appeared in the rare region (83%). However, the Target-Region effect was only marginally significant, $F(2, 28) = 3.18$, $p = .057$, $\eta_p^2 = 0.19$. While not statistically significant, this pattern aligns with the notion that suppressing the frequent distractor region also impacts the processing of targets appearing in that region – a conclusion that was also supported by the significant target-location effect on the manual RTs.

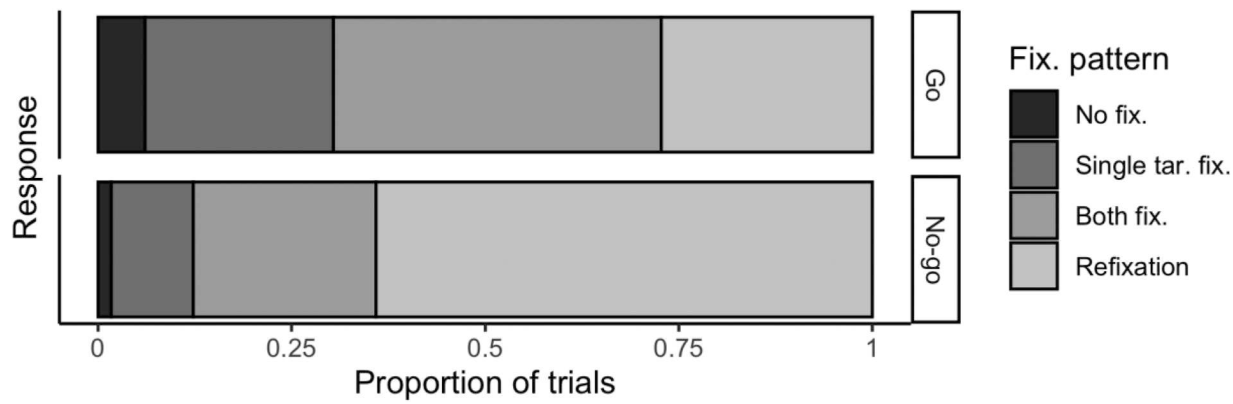

Figure 4. Proportion of trials with different target-fixation patterns: no fixation on either target ("No fix."), only one of the two targets fixated ("Single tar. fix."), both targets fixated without returning to the first target after fixating the second ("Both fix."), and both targets fixated followed by a return to the first target ("Refixation").

Fixations on the distractor. Participants' predominant scanning strategy was to inspect one target after the other. Given this, the distractor could have captured attention before inspecting any target (early stage), after inspecting the first target (intermediate stage), or after inspecting both targets (late stage of search). Accordingly, we examined whether distractors in the frequent region were – and stayed – suppressed during these stages of the trial. For this analysis, we focused on trials on which both targets were inspected (i.e., excluding the 27% of trials that had been classified as "no fixation" or "single target fixation"; see Figure 4). These trials were divided into four factorial conditions: Distractor Location (frequent vs. rare region) × Response Type (Go vs. No-go trials). For each condition, we then evaluated the proportion of trials in which the distractor attracted a saccade during each of the three stages: (1) prior to saccading to the first target, (2) in-between scanning the first and the second target, and (3) after inspecting both targets. The results are presented in Figure 5. Note that fixations on a distractor could happen multiple times during a single trial, and at different stages. This means that the cumulative proportion of fixations may exceed 100%.

Similar to the initial-fixation results reported above, the proportion of trials with a fixation on the distractor *before* the first target was substantially higher when the distractor appeared in the rare, rather than the frequent, region, $F(1,\ 14) = 8.2$, $p < .05$, $\eta_p^2 = .37$, – independently of the Response Condition

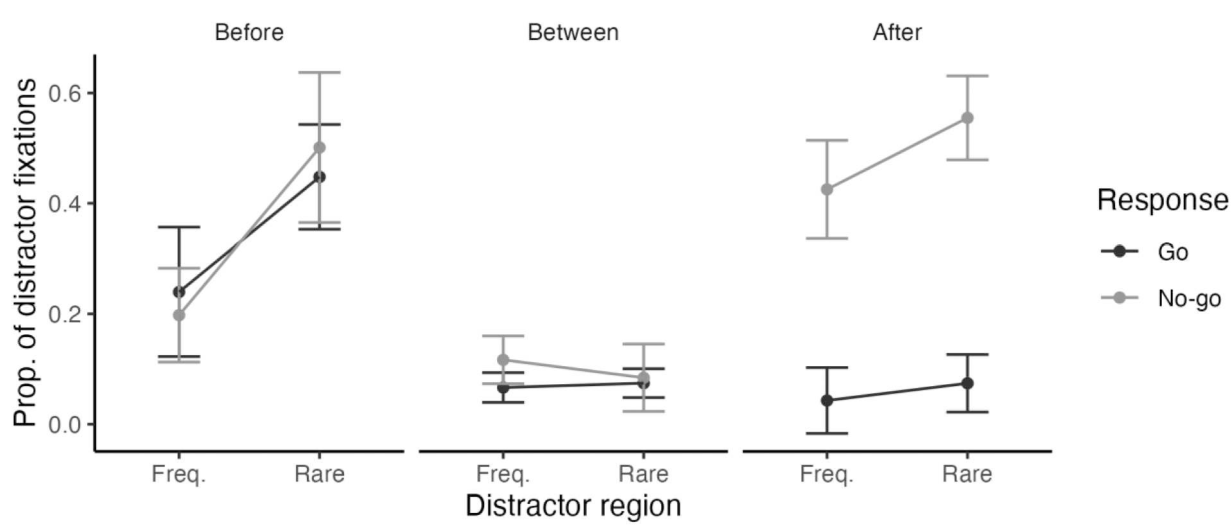

Figure 5. Proportions of trials in which there was at least one fixation on the distractor prior to inspecting the first target (Before), after inspection of the first target (Between), or, respectively, following inspection of both targets (After). Error bars indicate within-subject 95% confidence intervals (Cousineau, 2005).

(Main effect: F(1,14) = 0.027, $p = .87$, $\eta_p^2 = .002$, interaction: $F(1, 14) = 3.3$, $p = .09$, $\eta_p^2 = 0.19$). Fixations on the distractor *in-between* inspection of the two targets were overall rare (some 9% of distractor-present trials), and there was no difference between trials dependent on the (rare vs. frequent) region of distractor occurrence ($F(1,14) = 0.17$, $p = .69$, $\eta_p^2 = 0.012$.). *After* scanning both targets, the distractor rarely captured the eyes on Go trials, most likely because participants would quickly respond after inspecting both targets, which terminated the trial display. However, the distractor did attract an eye movement quite frequently on No-go trials, $F(1, 14) = 82.1$, $p < .001$, $\eta_p^2 = .85$, as the trial display remained in view even after participants had inspected both targets and decided that this was a trial on which a response was to be withheld. Interestingly, under these conditions, the proportion of trials with one or more distractor fixations after fixating both targets was significantly increased with a distractor in the rare, compared to the frequent, region. This indicates that the frequent region remained suppressed even when the task was effectively completed (after inspecting both targets). The pattern was similar on Go trials, though the Region effect appeared to be less marked. Statistically, however, there was only a reliable main effect of Distractor Region, $F(1, 14) = 5.71$, $p < .05$, $\eta_p^2 = .29$, which was not significantly modulated by the Response Condition (interaction, $F(1, 14) = 3.7$, $p = .07$, $\eta_p^2 = 0.21$).

Because the distractor appeared in the frequent region in 90% of the trials, it is possible that saccades towards the distractor before the target were, in absolute terms, more common in the frequent region than in the rare region. Consequently, it is plausible that the reduced distractor fixations after both targets have been scanned were also influenced by "inhibition of return" (IOR; Müller & von Mühlenen, 2000; Wang & Klein, 2010). To differentiate IOR from probability-based suppression, we further compared the proportion of post-target (i.e., late-stage) fixations of the distractor (after scanning both targets) for trials with and without initial (i.e., early-stage) fixations separately. This analysis did not include trials classified as no-fixation or single-target-fixation, as well as the few trials with distractor fixations between the two targets, which yielded an exclusion of one participant. See Figure 6 for the results.

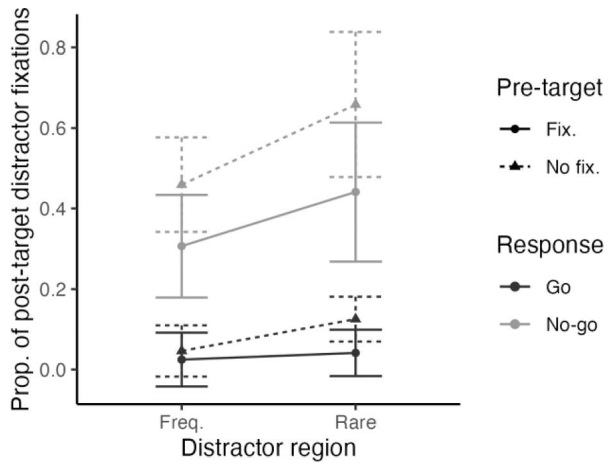

Figure 6. Proportions of post-target distractor fixations (i.e., fixations of the distractor after scanning both targets) for trials with (dots) and, respectively, without pre-target fixations of the distractor (triangles) as a function of the Region in which the distractor was located (Frequent vs. Rare), separately for Go (black) and No-go (gray) trials. Error bars indicate within-subject 95% confidence intervals (Cousineau, 2005).

As expected by IOR, there were overall fewer post-target fixations if the distractor was fixated prior to the target, $F(1, 13) = 13.5$, $p < .01$, $\eta_p^2 = 0.51$. Also, the effects of Distractor Region, $F(1,13) = 5.3$, $p < .05$, $\eta_p^2 = 0.29$, and Response Type, $F(1,13) = 76.1$, $p < .001$, $\eta_p^2 = 0.85$, were significant. The Region effect was due to a decrease in oculomotor capture by the distractor when the distractor appeared in the frequent region. The Response-Type effect was largely due to the extra time spent scanning on No-go trials. Critically, the interaction between the Pre-target-Fixation factor (i.e., whether or not the distractor was fixated prior to scanning the targets) and the Distractor Region was not significant, $F(1, 13) = 0.83$, $p = .38$, $\eta_p^2 = 0.06$. This pattern is indicative of probability-based distractor suppression in the frequent distractor region remaining active, even after the distractor was initially fixated at the beginning of a trial.

Finally, we examined whether (rapid) reactive suppression of distractors upon the initial (pre-target) capture would influence the time spent on distractors that attracted the eye after the scanning of the two targets (post-target fixation), by comparing the fixation duration of the initial pre-target distractor fixation and the late post-target first fixation (or re-fixation) of the distractor[5] (see Figure 7A). A repeated-measures ANOVA of the fixation duration on the distractor with the factors Distractor Region (frequent vs. rare), Response Type (Go vs. No-go)

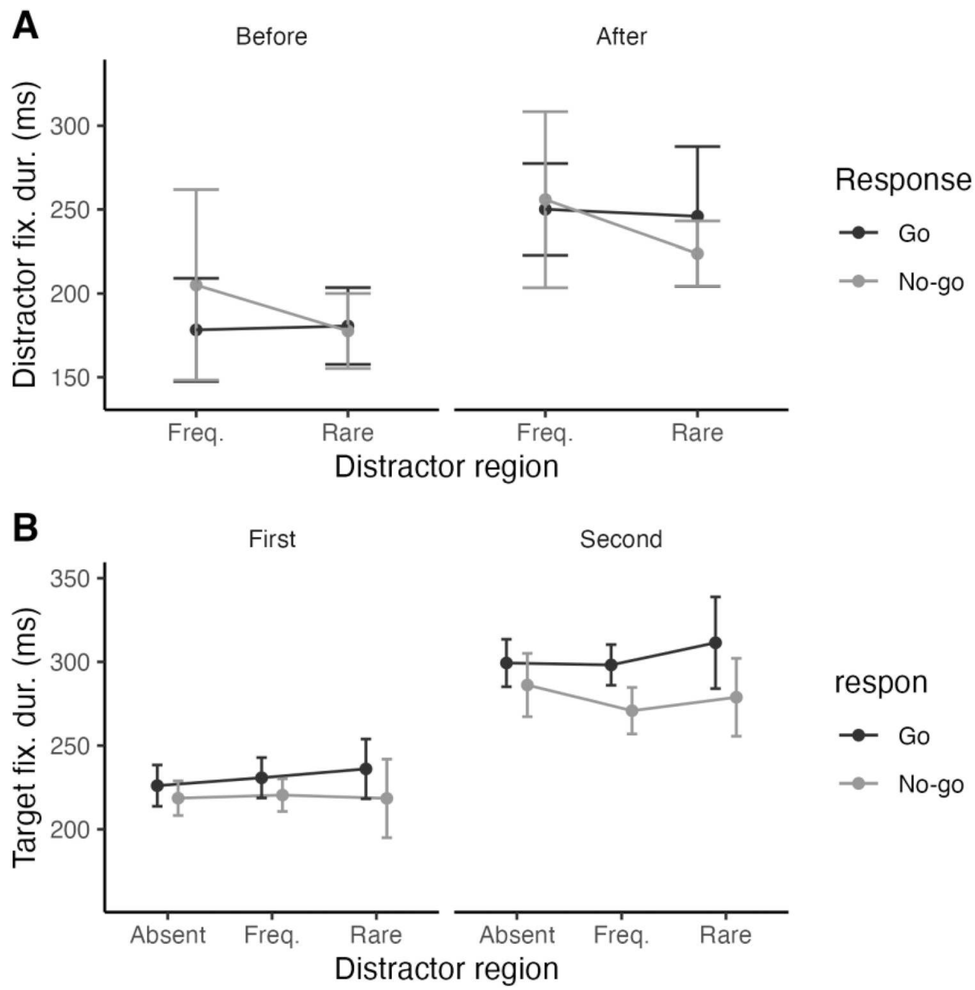

Figure 7. (A) Durations of first fixations on the distractor, before fixating the first target and, respectively, after fixating both targets. (B) Durations of first fixations on the first and, respectively, the second target. The durations are shown as a function of the distractor appearing in the frequent and rare region, separately for Go and No-go trials. Error bars indicate within-subject 95% confidence intervals (Cousineau, 2005).

and Fixation Type (pre-target vs. post-target) as factors revealed a significant main effect of Fixation Type, $F(1,10) = 13.0$ $p < .01$, $\eta_p^2 = 0.57$. The fixation duration was, on average, 59 ms longer for the post-target compared to the initial distractor fixation. That is, the fact that the distractor had already been rejected initially as task-irrelevant did not shorten the time spent on it on the late re-fixation; rather, the late fixation was prolonged. This longer re-fixation time was likely a result of a task-related confirmation process, ascertaining that the initial distractor rejection was accurate (see details in the Discussion section). Neither the main effect of Distractor Region ($F(1,10) = 1.46$ $p = .26$, $\eta_p^2 = 0.13$) nor that of Response Type ($F(1,10) = 0.025$, $p = .88$, $\eta_p^2 = 0.002$) were significant[6], and there were no significant interactions (*F*s < 2.5, *p*s $> .15$, $\eta_p^2 < 0.19$).

We also analyzed the durations of target fixations, comparing the durations of the (first) fixation on the first and the second target (see Figure 7B). A repeated-measures ANOVA with the factors Distractor Region (frequent vs. rare), Response Type (Go vs. No-go), and Target (target fixated first vs. target fixated second) revealed a significant main effect Target ($F(1,14) = 79.8$, $p < .001$, $\eta_p^2 = .85$): fixations on the second target (291 ms) were significantly longer than fixations on the first target (225 ms). There was also a non-significant trend towards longer fixation durations in the Go vs. the No-go condition (267 ms vs. 249 ms; $F(1,14) = 4.36$, $p = .056$, $\eta_p^2 = .24$). No other effect approached significance (all *F*s < 2, *p*s $> .2$). This pattern is interesting: The prolonged fixations on the second target likely reflect the fact that the decision whether or not to respond can only be made upon extraction of the response-relevant information from the second target (as this decision involves a comparison, establishing information congruence/incongruence, with the first target). And the prolonged fixation duration on the second target on Go trials is likely to reflect the fact that Go trials involved an additional two-alternative forced-choice decision (whereas No-go trials simply required withholding of a response).

Lastly, we compared the (initial and re-) fixation durations on the distractor to those on the (first and second) targets, averaging over distractor region and response condition.[7] This comparison revealed the distractor fixations to be generally shorter. Specifically, the duration of the initial distractor fixation was 36 ms shorter compared to the fixation on the first target (185 ms vs. 221 ms, $t(10) = -3.4$, $p = .007$), and the duration of the re-fixation of the distractor was 46 ms shorter than duration of the fixation on the second target (244 ms vs. 290 ms, $t(10) = -4.49$, $p = .001$). This pattern is indicative of relatively rapid distractor rejection, likely reflecting the fact that establishing a selected distractor as an irrelevant item only required determining its orientation (without the need to extract any response-relevant i-dot information).

Experiment 2

In Experiment 1, persistent regional distractor suppression of the frequent distractor region was observed even after viewing both targets (on No-go trials), that is, at a time when – one might assume – no further inspection of the targets would be required to make a manual forced-choice response (as the No-go decision has already been made). However, the possibility of a further decision confirmation process cannot be ruled out completely. For instance, participants might have been uncertain about their initial No-go decision and needed to recheck the first target before making a final decision. To eliminate such a rechecking possibility, in Experiment 2 we removed the response-critical feature (dots on target items) a fixed amount of time into a trial (1500 ms after search-display onset) by filling in the gaps of all search display items, transforming them from i-shaped items into solid bars. The 1500 ms cutoff was chosen based on how long it took participants to fixate both targets in Experiment 1. Specifically, participants fixated both targets within 1500 ms on 95% of trials. This cutoff ensured that most participants on most trials would have sufficient time to locate both targets and obtain the information needed for a response, while also applying some time pressure and discouraging re-checking the first target after locating the second target.

Methods

Participants

A new group of 16 (9 female) healthy university students (Mean age = 26.6, SD = 4.2) was recruited, meeting all ethical requirements, and receiving monetary compensation as in Experiment 1. The required effect size and subsequent sample size were consistent with those of Experiment 1.

Apparatus and stimuli

Experiment 2 was conducted in the same sound-attenuated and dimly lit laboratory cabin and utilized the same monitor as in Experiment 1. The items (2.025° of visual angle in total length, 0.375° in width) looked the same as in Experiment 1 ("i"-shaped with a small gap at one end) upon initial presentation of the search display. However, in the second half of the (maximum) visual display period (i.e., 1500 ms after display onset), the small gap in the stimuli was removed in all items, turning them into "I"-shaped stimuli. Further, the proportion of distractor-present trials was increased, resulting in more (theoretically most interesting) distractor-present trials compared to distractor-absent trials, 70% versus 30%, out of the total 1008 trialsö and the proportion of theoretically interesting no-go trials was increased to 40%.

Procedure

Experiment 2 closely followed the design of Experiment 1, with two major changes: the search display and display exposure time. Following the presentation of the fixation dot for 700–1100 ms, the search display appeared. The display was initially the same as in Experiment 1 (Figure 1, panel B), but changed into a "masked" display – in which all items had an "I" shape – after 1500 ms (Figure 1, panel C); that is; after the initial 1500 ms, the display no longer contained any response-critical features, effectively making rechecking of task decisions reached by that time impossible. The masked display also lasted for up to another 1500 ms, yielding the same total maximum display time as in Experiment 1. The search display disappeared upon the participant's response if a response was issued prior to the maximum display time.

Results

Behavioural results

Mean accuracy in Experiment 2 was slightly lower than in Experiment 1 but still relatively high (mean: 92.5%, range: 68-99%) and did not differ significantly between Go (92.4%) and No-go (92.6%) trials. RTs on Go-trials (see Figure 8A) were slower for trials with a distractor in the rare compared to the frequent distractor region (1245 vs. 1203 ms; $t(15) = 2.13$, $p = .050$)[8], while accuracy (Figure 8B) was comparable between the two conditions (91.1% vs. 91.5%; $t(15) = -0.44$, $p = .67$). As for Experiment 1, we analyzed RTs on distractor-absent trials as a function of the distractor region(s) in which the two targets appeared: both in the frequent region, both in the rare distractor region, or one in the frequent and one in the rare region (see Figure 8C). A repeated measures ANOVA revealed a significant effect of the Target Location, $F(2, 30) = 9.29$, $p < .001$, $\eta_p^2 = .38$. RTs were significantly slower when both targets appeared in the frequent region compared to when both appeared in the rare region ($t(15) = 4.1$, $p < .001$), and also slower when one target appeared in each region compared to when both appeared in the rare region ($t(15) = 3.2$, $p = .009$). There was no significant difference between "both targets in the frequent region" and "one target in each region" ($t(15) = .83$, $p > .99$).

Overall, the behavioural results were similar to those in Experiment 1, with both a distractor-location effect and a target-location effect, although the distractor-location effect was somewhat smaller (42 ms) compared to in Experiment 1 (117 ms), attributable to the masking of the search display after 1500 ms.

Eye-tracking results

First fixations. Like in Experiment 1, the initial saccades mostly landed either on one of the targets or on the distractor. During trials without a distractor, 79% of the initial saccades landed on the target. In contrast, when a distractor was present, 58% of the initial saccades landed on a target, while 25% landed on the distractor. To investigate the effects of distractor region, trials with a distractor were subdivided based on the region in which the distractor appeared (the frequent or the rare distractor region) and the response condition (see Figure 9). Initial saccades landed on the distractor less frequently when the distractor appeared in the frequent compared to the rare region (23% vs. 46%, $F(1,15) = 6.84$, $p = .019$, $\eta_p^2 = .31$), with a corresponding increase in target fixations (60% vs. 39%, $F(1,15) = 6.52$, $p = .022$, $\eta_p^2 = .30$). No other effects were statistically significant. These results closely mirror those of Experiment 1, suggesting that the removal of the response-critical information halfway through a trial did not interfere with regional distractor-suppression learning.

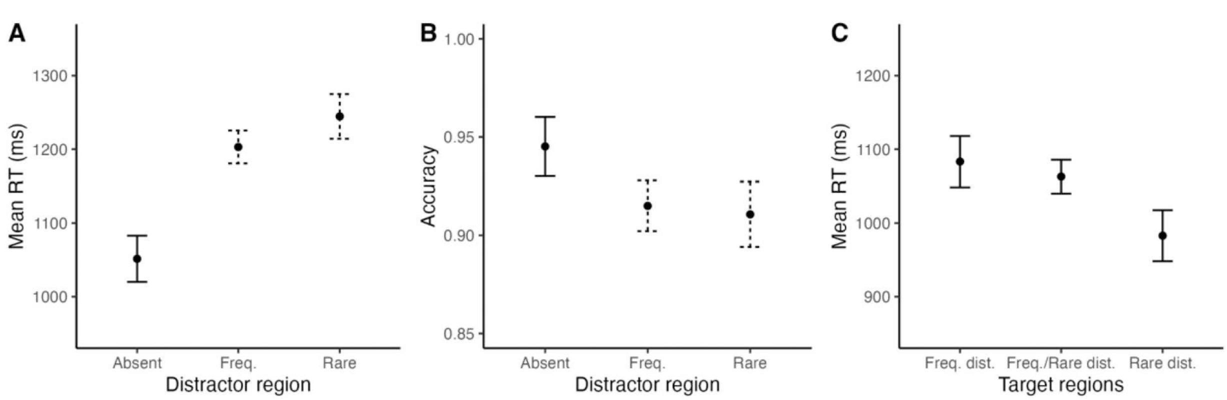

Figure 8. Mean "Go"-trial RTs in milliseconds (A) and mean response accuracies in percent (B) for the three Distractor conditions (distractor absent, distractor in frequent region, distractor in rare region), as well as RTs on distractor absent trials for trials with targets in the frequent distractor region ("Freq. dist"), the rare distractor region ("Rare dist."), or both regions (C) in Experiment 2. Error bars indicate within-subject 95% confidence intervals (Cousineau, 2005).

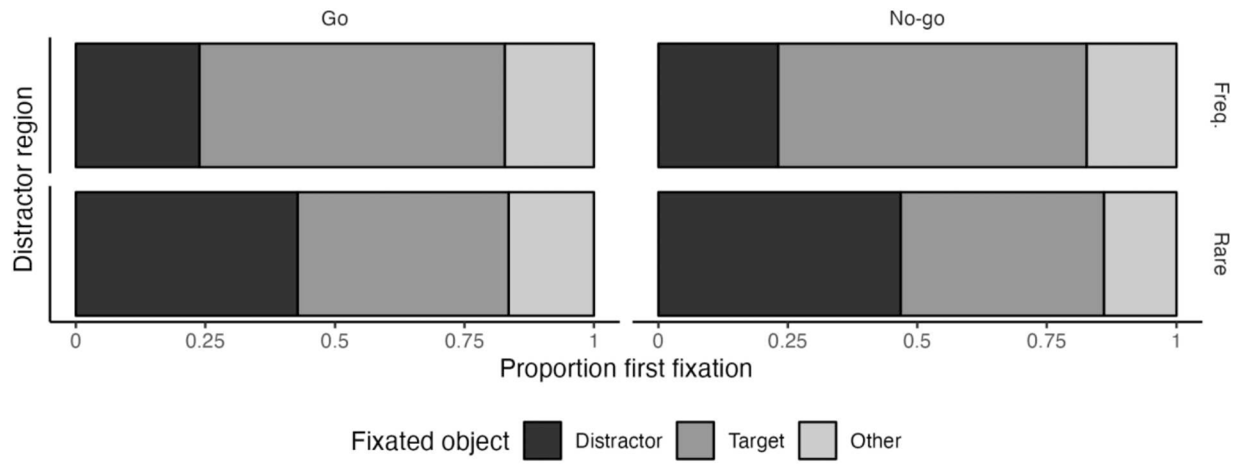

Figure 9. Proportions of first fixations on the distractor, the target, or "another" item in Experiment 2, on trials with a distractor in the frequent region (upper panels) or the rare region (lower panels), separately for Go trials (left panels) and No-Go trials (right panels).

Fixations on targets. Similar to Experiment 1, we categorized trials into four target-fixation patterns ("no-fixation", "single-target-fixation", "both-target-fixation" and "target re-fixation", Figure 10). During go-trials, the "both-target-fixation" pattern, where participants fixated on each target once, was the most common (48%). Conversely, in no-go trials, the "target re-fixation" pattern, characterized by fixating both targets and then returning to the first one, was more prevalent (51%). This pattern suggests that even after removing response-critical information at 1.5 s, participants utilized the additional time on no-go trials to re-examine the targets, albeit to a lesser extent compared to Experiment 1, where the proportion of no-go trials with the re-fixation pattern was higher at 64%.

We further examined the proportions of first fixations on the target on distractor absent trials as a function of the region in which the target appeared. A repeated measures ANOVA revealed a marginally significant target region effect, $F(1.3, 19.4) = 3.65$, $p = .062$, $\eta_p^2 = .20$ (Greenhouse-Geisser corrected degrees of freedom), aligning with the findings of Experiment 1.

Fixations on the distractor. To gain deeper insights into the dynamics of distractor suppression over the course of each trial, we conducted an analysis similar that performed on the data from Experiment 1. Specifically, we analyzed the proportion of trials with a distractor fixation during three distinct stages: (1) before making a saccade to the first target, (2) between scanning the first and second targets, and (3) after examining both targets (see Figure 11). In this analysis, we only included trials in which both targets were fixated (i.e., trials with the

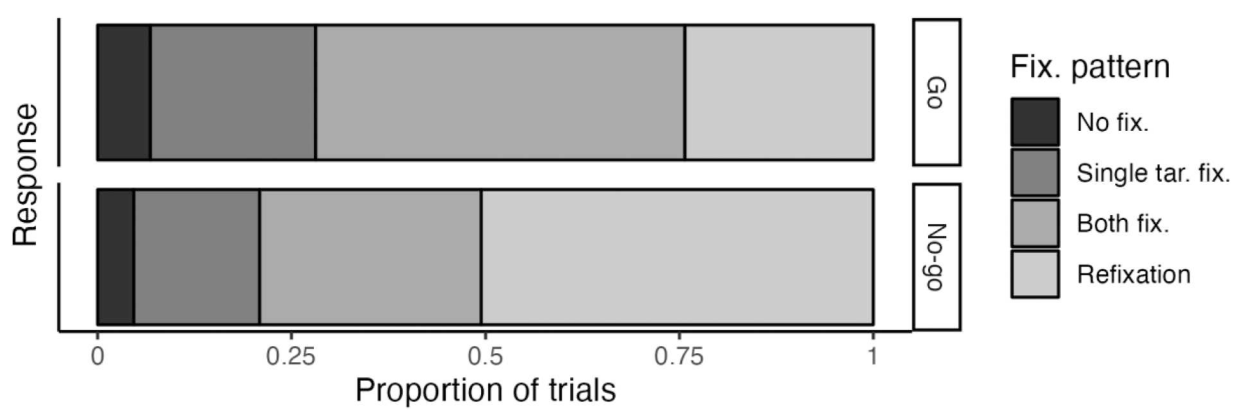

Figure 10. Proportion of trials with different target-fixation patterns: no fixation on either target ("No fix."), only one of the two targets fixated ("Single tar. fix."), both targets fixated without returning to the first target after fixating the second ("Both fix."), and both targets fixated followed by a return to the first target ("Refixation") in Experiment 2.

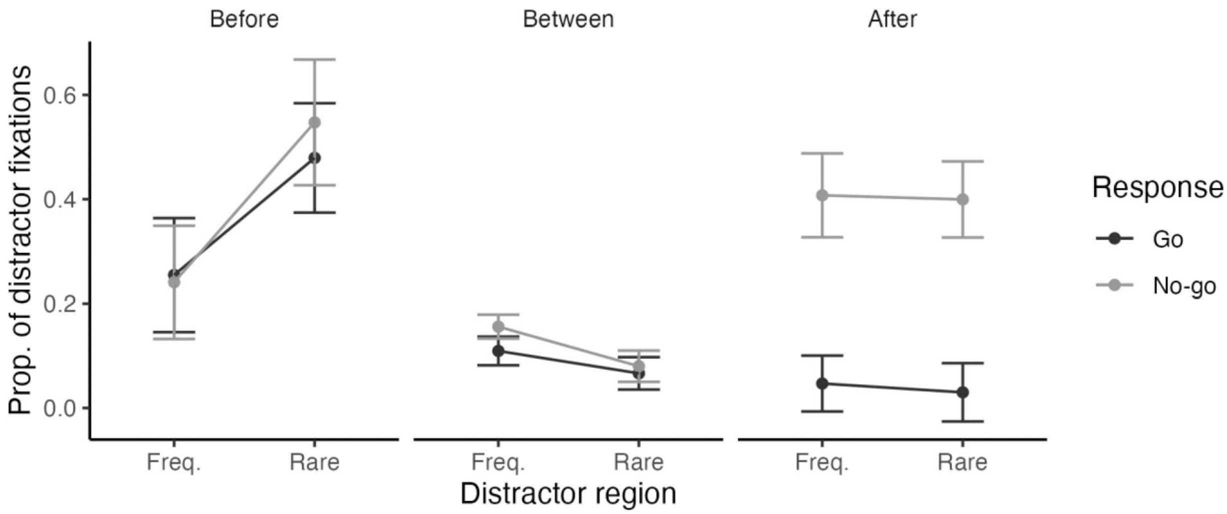

Figure 11. Proportions of trials in Experiment 2 in which there was at least one fixation on the distractor prior to inspecting the first target (Before), after inspection of the first target (Between), or, respectively, following inspection of both targets (After). Error bars indicate within-subject 95% confidence intervals (Cousineau, 2005).

"No fix." or "Single tar. fix." patterns were excluded, which comprised 25% of trials in total; see Figure 10).

The proportion of trials on which the distractor was fixated before any fixation on the target was significantly higher for trials with a distractor in the rare compared to the frequent distractor region, $F(1,15) = 7.39$, $p = .016$, $\eta_p^2 = .33$. This is consistent with the initial-fixation results and the results of Experiment 1. Interestingly, there was also a significant interaction with the response condition, $F(1, 15) = 8.14$, $p = .012$, $\eta_p^2 = .35$, resulting from a somewhat larger distractor location effect on No-go (31%) compared to Go trials (23%).

Fixations on the distractor in-between inspecting the two targets, while overall relatively rare (10% of trials), followed the opposite pattern: the proportion of fixations was significantly higher for trials with a distractor in the frequent compared to the rare region, $F(1,15) = 8.26$, $p = .012$, $\eta_p^2 = .36$. The proportion of between-target distractor fixations was also significantly higher on No-go compared to Go trials ($F(1,15) = 5.30$, $p = .036$, $\eta_p^2 = .26$); and there was a significant interaction ($F(1,15) = 5.38$, $p = .035$, $\eta_p^2 = .26$), resulting from a larger location effect on No-go trials (7.6%) compared to Go trials (4.3%). These results are different compared to Experiment 1, where there was no significant location effect for between-target distractor fixations.

Lastly, we analyzed the proportion of distractor fixations following fixations of both targets. The proportion of post-target fixations was significantly higher on No-go than on Go trials, $F(1,15) = 57.2$, $p < .001$, $\eta_p^2 = .79$, which is expected given the longer display exposure durations on No-go trials, like in Experiment 1. However, the most notable and interesting difference compared to Experiment 1 was the absence of post-target probability-cueing effect, indicated by the absence of a difference in the proportion of fixations between trials with a distractor in the frequent compared to the rare region, $F(1,15) = .23$, $p = .64$, $\eta_p^2 = .015$. This is theoretically important: it suggests that when response-critical information is removed, eliminating the need, or opportunity, to re-check previously inspected targets or continue searching, regional distractor suppression may be deactivated.

The absence of a probability-cueing effect at the post-target-fixation stage might be attributed to differential IOR in the two regions. Even though Experiment 1 suggests this is unlikely, we investigated this by subdividing trials on which both targets were fixated into two categories: those with a distractor fixation before any target fixation and those without. We then analyzed the proportions of trials with a distractor fixation after fixating both targets[9] (see Figure 12A). While the proportions of fixations were comparable in the two regions, $F(1,14) = 0.0003$, $p = .99$, $\eta_p^2 = .00002$, they were significantly higher on trials without relative to trials with any pre-target distractor fixation ($F(1,14) = 8.45$, $p = .011$, $\eta_p^2 = .38$) – an outcome indicative of IOR. However, there was no significant interaction with Distractor Region ($F(1,14) = 0.037$, $p = .85$, $\eta_p^2 = .003$).

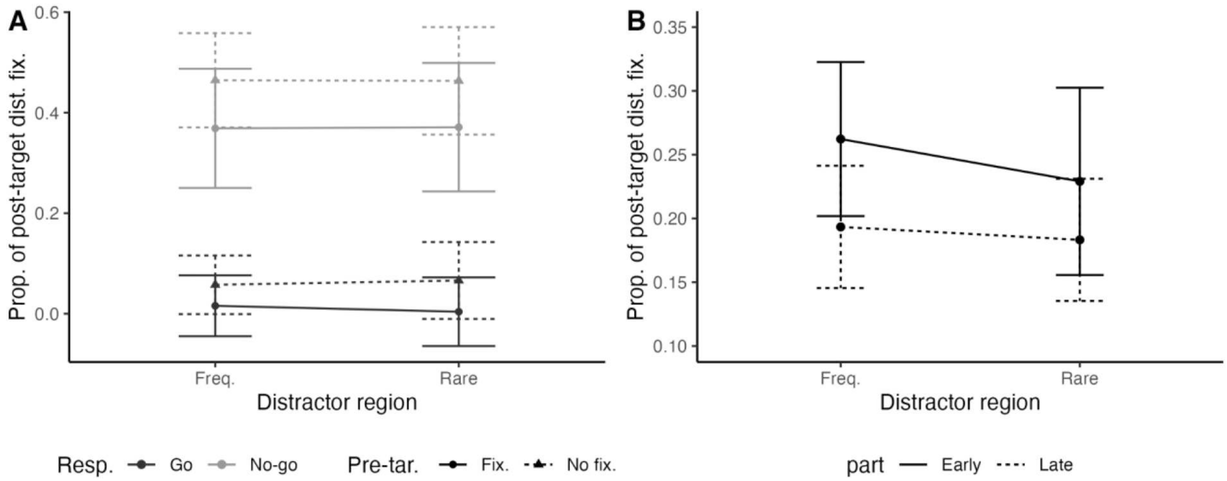

Figure 12. (A) Proportions of post-target distractor fixations (i.e., fixations of the distractor after scanning both targets) for trials with (dots) and, respectively, without pre-target fixations of the distractor (triangles) as a function of the Region in which the distractor was located (Frequent vs. Rare), separately for Go (black) and No-go (gray) trials. (B) proportions of post-target distractor fixations on no-go trials as a function of the Region in which the distractor was located (Frequent vs. Rare distractor region), separately for fixations the early part of each trial (before removal of the response-critical information) and the late part of each trial (after removal of the response-critical information). Error bars indicate within-subject 95% confidence intervals (Cousineau, 2005).

One might argue that the absence of a post-target probability-cueing effect is due to a participants changing their decision strategy following the removal of the response-critical feature, such as making fewer re-fixations on a target. This could also influence how often participants' attention was captured by the distractor. To rule this out, we compared "early" and "late" fixations, which were demarcated by the onset of the masking display (see Figure 12B). Across both conditions, on trials with a distractor in the frequent region, there was a numerically higher proportion of trials with an (early or late) distractor fixation compared to trials with a distractor in the rare region. However, this difference was not significant (Early: 26% vs. 23%, $t(15) = 0.85$, $p = .41$; Late: 19% vs. 18%, $t(15) = 0.23$, $p = .82$). The similar proportions of (early and late) distractor fixations for trials with a distractor in the frequent compared to the rare region and the continued high number of fixations on distractors, irrespective of the distractor region, even after eliminating the response-critical information, implies that distractor suppression may no longer have been engaged when the response-critical information was removed.

Finally, to ascertain whether the distinct patterns observed in Experiments 1 and 2 reflect a genuine difference between experiments, we performed a mixed-effects ANOVA on the proportions of post-target fixations falling on the distractor (i.e., distractor fixations on trials on which both targets had already been fixated) from both experiments. Distractor Region and Response Condition (Go or No-go) were included as within-participant factors, with Experiment (1, 2) as a between-participant factor (see Figures 5 and 11). There was no significant main effect of Distractor Region ($F(1,29) = 2.61$, $p = .12$, $\eta_p^2 = .08$) or Experiment ($F(1,29) = 1.74$, $p = .20$, $\eta_p^2 = .06$), but the interaction was significant ($F(1,29) = 4.85$, $p = .036$, $\eta_p^2 = .14$), resulting from the significant distractor-location effect in Experiment 1 but not in Experiment 2 (as shown in the previous analyses). These results are consistent with the hypothesis that the regional distractor suppression remained active throughout the entire trial in Experiment 1, but was deactivated after the removal of the response-critical information in Experiment 2.

General discussion

The present study was designed to examine how learned, location-based distractor suppression plays out over time after the onset of a search display. To this end, we introduced a task in which participants had to search for, and discriminate, two targets in order to decide upon the response – either a 2AFC "Go" response, if the i-dots in the two targets were congruently positioned (both on top or both on the bottom), or a "No-go" response, if the positions of the dots were incongruent. Under the latter condition, the display exposure was extended to 3,000 ms, allowing us to observe ongoing scanning behaviour even after the response decision had been made (some 1000–1200 ms, judging from the RTs on Go trials). The salient distractor was defined by maximum feature contrast in the same – orientation – dimension as the target, to ensure that distractor suppression (likely) operated at the level of the priority map (see also Ferrante et al., 2018; Liesefeld & Müller, 2021; Wang & Theeuwes, 2018); and, if present, the distractor was 9 times more likely to appear at one particular, "frequent" display region compared to the other, "rare" region. In addition to RTs (on Go trials), we also recorded and examined participants oculomotor search behaviour on both Go and No-go trials.

As regards the RT effects (in the Go condition), we replicated the well-established distractor-location effect, as well as finding the predicted target-location effect: RTs were substantially faster when the distractor appeared at a location in the frequent (vs. the rare) region (on distractor-present trials); conversely, they were slower when the two targets appeared at locations in the frequent (vs. the rare) region (with RTs being in-between when one target appeared in the frequent and the other in the rare region). This pattern is consistent with a plethora of previous studies, which have taken the distractor-location probability-cueing effect (along with the target-location effect) to be indicative of proactive suppression of the likely distractor location(s) based on statistically acquired "predictions" (Allenmark et al., 2021, 2022; Di Caro et al., 2019; Ferrante et al., 2018; Sauter et al., 2018, 2021; Wang et al., 2019; Wang & Theeuwes, 2018; Zhang et al., 2019). Further evidence for this interpretation comes from our eye-movement results: While the distractor often captured participants' eyes before they fixated on one of the two targets, oculomotor capture of the first saccade was less likely when the distractor occurred in the frequent vs. the rare region (an effect seen of both Go an No-go trials). This provides oculomotor evidence of proactive suppression, consistent with previous eye-movement studies (Di Caro et al., 2019; Kim & Anderson, 2022; Sauter et al., 2021).

Going beyond recent studies of oculomotor capture, which all used single-target tasks, we further analyzed oculomotor capture by the distractor both between the inspection of two targets and after inspecting both. We found that on No-go trials (with the extended viewing time), a robust distractor-region effect re-emerged after inspection of the second target when the response-critical information was still available (Experiment 1), but this effect was no longer evident when the response-critical information was removed halfway through each trial (Experiment 2). This suggests that the statistically learned proactive suppression is rather phasic in nature: it remains active as long as necessary to solve the task, but can be flexibly disengaged when the response-critical decision has been made and/or there is no longer an opportunity to re-check the decision. This pattern is in line with previous findings that proactive suppression is activated only upon display onset, and is distinct from anticipatory suppression (Noonan et al., 2016; Qiu et al., 2023; van Moorselaar et al., 2020). Thus, converging evidence suggests that statistically learned distractor suppression is proactive in nature, but its use is flexible, depending whether the system requires it or not.

Importantly, in the presence of response-critical information, the distractor-region effect was evident even when we focused on trials in which the distractor attracted the eye only late (after inspection of the two targets) – ruling out IOR-type reactive suppression being responsible for this pattern. IOR-type suppression was evident in an overall reduced proportion of late capture incidents on trials on which the distractor had already been fixated earlier on. But the IOR-type suppression proved to be an additive factor, independent of the acquired Distractor-Region effect.

While we have here interpreted the distractor-region effect in terms of "suppression", another possible interpretation would be that distractors in the rare region tend to strongly capture attention because they are "surprising", while distractors in the frequent region capture less attention due to "habituation" (Poon & Young, 2006; Sokolov, 1963; Thompson, 2009; Turatto, 2023). It is beyond the scope of the present study to distinguish between suppression and habituation accounts of the distractor-region effect. However, our results show that whatever process underlies the distractor-region effect, it can be flexibly activated during a task and deactivated during task-free exploration. While there is some evidence that habituation can be context-dependent (e.g., Turatto et al., 2018, 2019), the flexible activation and deactivation of distractor-location effects based on current task requirements is, to our knowledge, not a prediction of current theories of habituation.

Another interesting finding is that fixations on the distractor were longer after inspecting both targets (late stage) compared to before attending to the first target (early stage). Longer fixations at the late stage would be more in line with the notion of phasic suppression, according to which the distractor holds the eye and attention longer once the "wave" of suppression has subsided. Additionally, this extended fixation duration at late stage might result from a more thorough re-checking, post the response decision, to ensure the correct item had been selected and the incorrect item rejected for completing the task. Also, participants might have intended to gaze back at the first target after locating both targets to verify whether their i-dot positions were the same or different, but their eyes were inadvertently attracted by the distractor. In this case, the re-fixated distractor might have been mistaken for a target, taking longer to be identified and rejected as a distractor.

However, the fixation duration was similar between distractor regions (frequent vs. rare regions) at both the early and late stages. The absence of a probability-cueing effect in fixation durations contrasts with previous oculomotor capture studies (Sauter et al., 2021; Wang et al., 2019). Some studies found shorter initial fixations on the distractor in frequent relative to rare regions, attributing this to expedited disengagement of eyes from distractors at "suppressed" locations. Of note, the task in these studies required participants to find only one response-critical target, while our study required attention to two, equally salient targets. This task difference could explain the lack of a fixation-duration effect. In our task, when a participant's attention had been captured by the distractor, they needed to do more than just disengage from the distractor, that is: make a decision confirming that the fixated item was in fact a distractor rather than a target, and then decide which of two equally salient targets to move to next. If resolving the competition between the two equally strong priority signals of the two targets takes longer than the disengagement from the distractor, and if the decision about where to move next and the disengagement from the distractor occur in parallel, with the next saccade initiated only once both processes are complete, then any effect on disengagement might be "masked" by the longer decision time needed for choosing between the two targets.

Another noteworthy finding is that, on trials in which the distractor was not fixated before the first target, it barely ever attracted the eye in-between inspection of the first and the second target (and these rare capture incidents showed no Distractor-Region effect in Experiment 1 and a reversed Distractor-Region effect, i.e., more frequent capture by distractors in the frequent region, in Experiment 2). The few capture incidents after fixating the first target might be attributable to reactive suppression. Even though the distractor had not summoned an overt eye movement initially (prior to the first target), it is possible that (on many of those trials) it might have captured attention covertly, and that this could have triggered reactive suppression. On trials in which the distractor did capture overt attention before the first target, a re-fixation of the distractor was more rare, compared to when there had been no prior overt capture, consistent with inhibition of return (IOR). Importantly, at least in the No-go condition (Experiment 1), a marked Distractor-Region (probability-cueing) effect remained even after the initial oculomotor capture, suggesting that IOR combines close to additively with the suppression underlying the probability-cueing effect (in the Go condition, there is some evidence of a floor effect, with almost no distractor fixations in either distractor region after inspection of both targets).

In conclusion, we confirmed the classical distractor-location probability-cueing effect and the target-location effect. Using eye-tracking and a dual-target task with extended presentation time, we observed that the proportion of distractor fixations was greatly reduced for distractors in the frequent compared to the rare region. This reduction occurred both before and after target fixations, as long as the response-critical feature was available, manifesting the distractor-region effect. Importantly, this proactive suppression was independent of the reactive IOR. However, the statistically learned suppression was turned off when the response-critical feature was absent. This pattern supports the idea that learned distractor-region suppression operates flexibly, depending on the prevailing task requirements: the suppression mechanism remains in operation while performing the task, but is deactivated during task-free exploratory search. This is consistent with the notion that whether or not distractor suppression is invoked is under cognitive control (see also Müller & von Mühlenen, 2000), that is, in the present study: tied to an active task set, rather than being a completely automatized process. This might also explain recent reports that the operation of suppression, or habituation, shows context-dependency (e.g., Moher & Leber, 2023; Turatto et al., 2018, 2019; but see Britton & Anderson, 2020), with the incidentally learned extraneous display context (such as the search display being superimposed on a natural or an urban scene) becoming part of the task-related triggering conditions.

Notes

1. We would like to thank an anonymous reviewer for a suggestion that formed the basis for the design of this experiment.
2. In Appendix B, we confirm that the distractor-location effect is still significant even if exact distractor location repetition trials are removed, demonstrating that this effect represents a longer-term effect resulting from distractor location learning, rather than being due merely to more frequent distractor-location repetitions.
3. Following the standard in analyses of the target-location effect (e.g.,Wang & Theeuwes, 2018), we tested for this effect on distractor-absent trials, i.e., under pure conditions in which there is no distractor competing with the targets for the allocation of attention.
4. We also examined the latencies of the first saccades to the distractor and, respectively, a target (see Appendix A for details). The latencies turned out some 30–40 ms shorter for distractor- vs. target-directed saccades (the latter on distractor-present trials), reflecting the difference in saliency between the two types of "singleton". Target-directed saccades were somewhat faster when there was no distractor in the display (i.e., on distractor-absent trials), compared to distractor-present trials. In other words, saccades to the target were delayed by the presence of a distractor even if the distractor did not capture the eye – indicative of covert attentional processes to resolve the competition.
5. To conduct this analysis, we only included trials on which both targets and the distractor were fixated. We computed the duration of fixation on the distractor during these trials (including the duration of multiple fixations if there were any). This was done both before and after fixation of both targets. However, we had to exclude four participants as they did not have any trials in one of the conditions.
6. Analyses of the total fixation duration and the average duration on the distractor yielded similar results.
7. For this analysis, we again excluded the same four participants who had to be excluded from the analysis of the distractor fixation durations.
8. In Appendix B, we confirm that a marginally significant distractor location effect remains when exact distractor location repetition trials are removed.
9. For this analysis we excluded trials with a distractor fixation in between the two target fixations, and we excluded one participant who did not have any valid trials in one of the conditions.

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Open practices statement

All data are available at: https://github.com/msenselab/suppression_duration.

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Appendices

Appendix A: Latencies of first saccades to the distractor and, respectively, target

We also examined the latencies of the first saccades to the distractor and, respectively, a target (Figure A1). Trials on which the saccadic latency was shorter than 50 ms or longer than 500 ms were excluded from this analysis, as was one participant who did not have any valid trials in one of the conditions. Since we did not expect the first saccade to be influenced by the (Go/No-go) response condition (as participants could only know the condition after inspecting both targets) and the analysis of the proportions of first fixations had revealed no difference, we collapsed the data across both response types to have enough trials in each condition of interest.

A repeated-measures ANOVA on the *target* saccadic latency yielded a significant main effect of Distractor Region ($F(1.21,15.8) = 5.18$, $p = .032$, $\eta_p^2 = .29$, Greenhouse-Geisser correct degrees of freedom). Bonferroni corrected post-hoc tests revealed the saccadic latency to be significantly shorter on distractor-absent trials, compared to trials with a distractor in the rare region ($t(13) = 3.22$, $p = 0.01$). No other

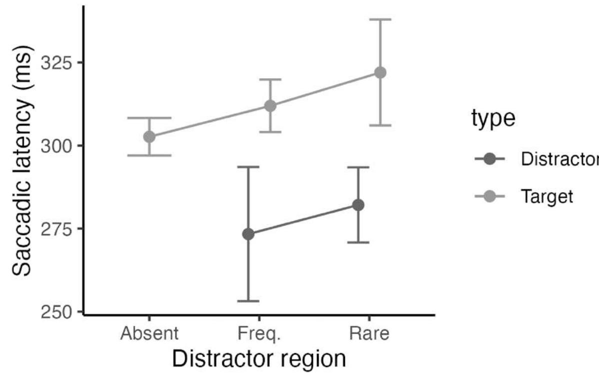

Figure A1. Saccadic latencies to the target and distractor on trials with a distractor in the frequent or rare region, or without a distractor in the display (for the target latencies). Error bars indicate within-subject 95% confidence intervals.

comparison was significant ($t < 2$, $p > 0.3$). There was no significant Distractor-Region effect for the *distractor* latencies ($F(1,13) = 0.68$, $p = .43$, $\eta_p^2 = .05$). Averaged across the distractor-region conditions, saccadic latencies to the distractor were significantly shorter than latencies to the target (278 ms vs. 312 ms, $t(13) = 4.1$, $p = .0012$).

Appendix B: Inter-trial effect analyses

One potential concern is that the distractor location effect may be a result of inter-trial effects. Since distractors appear more frequently in the frequent distractor region, repetitions of the exact same distractor location will also be more frequent in this region. Assuming that participants tend to suppress the location on which the distractor occurred on the previous trial, a distractor location effect would be predicted based on suppression of the previous distractor location alone.

It should be noted that analyses from previous probability-cueing studies have already shown that the effects observed cannot be solely attributed to inter-trial effects (Goschy et al., 2014; Sauter et al., 2018). Nevertheless, to confirm that our distractor location effect was not merely due to such an inter-trial effect, but reflected longer-term learning, we repeated some of our analyses, related to the distractor location effect, with trials with an exact repeat of the distractor location removed (same analysis as Sauter et al., 2018).

Distractor location effect on RT

Figure B1 Shows the mean RTs in the three distractor conditions (distractor absent, distractor in frequent region, and distractor in rare region), with exact distractor location repetition trials removed, from both experiments. RTs were slower for trials with a distractor in the rare region compared to trials with a distractor in the frequent region in both experiments, although in Experiment 2 the difference was only marginally significant: (Exp 1: $t(14) = 6.64$, $p < .001$; Exp 2: $t(15) = 1.94$, $p = .072$). This is the same pattern of results which was observed when including the distractor location repetition trials.

Fixations on the distractor

Figure B2 Shows the proportions of trials, in both experiments, on which there was at least one fixation on the distractor prior to inspecting the first target (Before), after inspection of the first target (Between), or, respectively, following inspection of both targets (After), with exact distractor location repetition trials removed.

There was a significantly larger proportion of trials, but no significant interaction with the response condition, with a distractor fixation before fixating either target among trials with a distractor

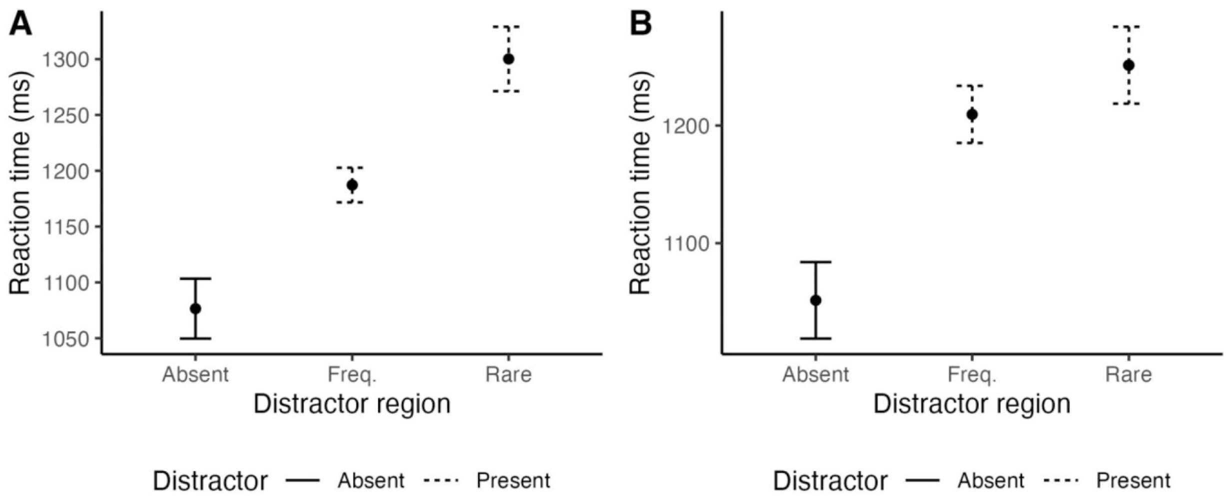

Figure B1. Mean "go"-trial RTs in milliseconds from Exp. 1 (A) and Exp. 2 (B) for the three Distractor conditions (distractor absent, distractor in frequent region, distractor in rare region), with exact distractor location repetition trials removed. Error bars indicate within-subject normalized 95% confidence intervals.

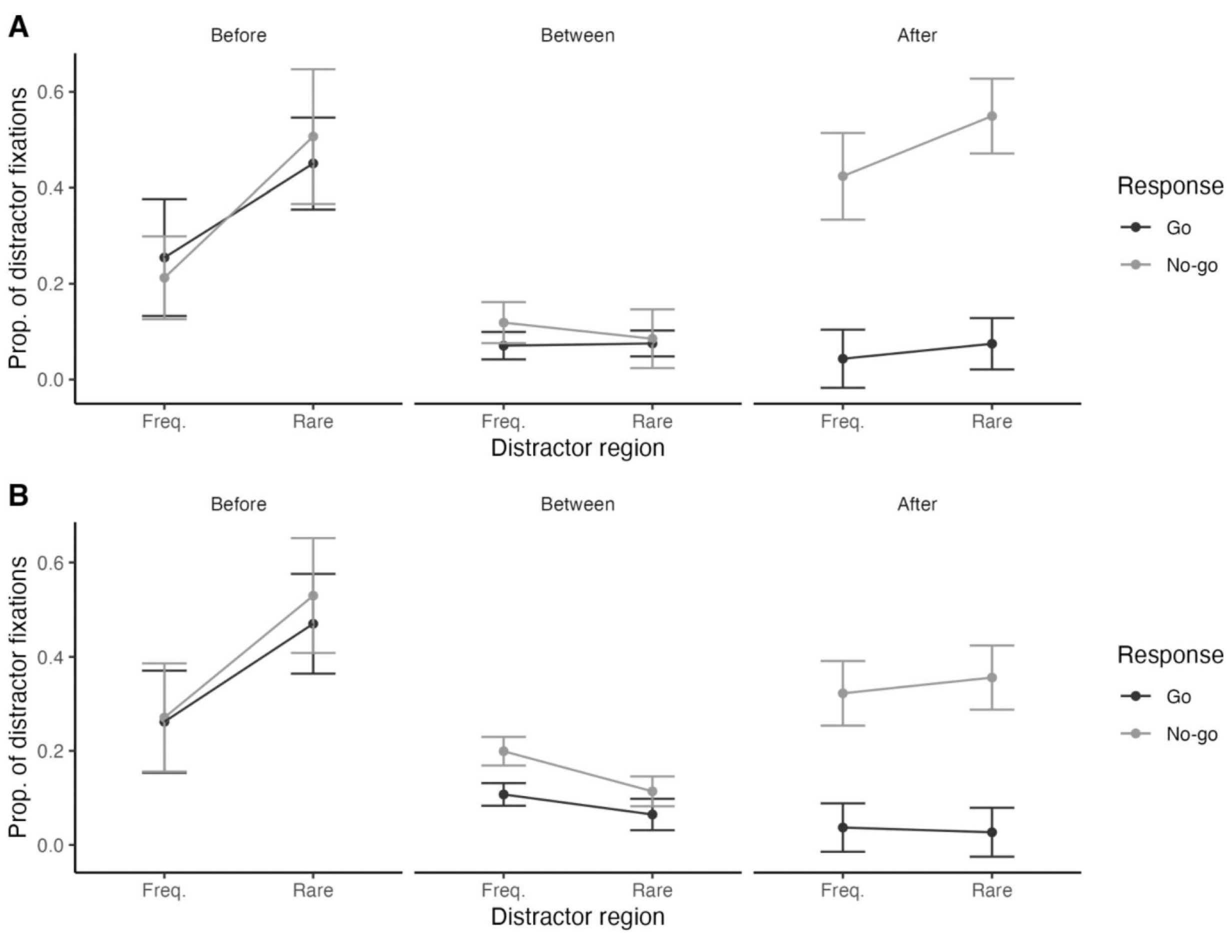

Figure B2. Proportions of trials in Experiment 1 (A) and Experiment 2 (B) on which there was at least one fixation on the distractor prior to inspecting the first target (Before), after inspection of the first target (Between), or, respectively, following inspection of both targets (After), with exact distractor location repetition trials removed. Error bars indicate within-subject normalized 95% confidence intervals.

in the rare compared to the frequent region in both Experiments (Exp 1: $F(1, 14) = 7.14$, $p = .018$; Exp 2: $F(1, 15) = 5.37$, $p = .035$). In Experiment 1, but not Experiment 2, there was also a significantly larger proportion of trials with a distractor fixation after fixating both targets among trials with a distractor in the rare compared to the frequent region (Exp 1: $F(1, 14) = 5.28$, $p = .037$; Exp 2: $F(1, 15) = 0.28$, $p = .60$). Finally, in Experiment 2, but not Experiment 1, there was a significantly smaller proportion of trials on which the distractor was fixated in-between fixations of the two targets among trials with a distractor in the rare compared to the frequent region (Exp 1: $F(1, 14) = 0.23$, $p = .64$; Exp 2: $F(1, 15) = 14.59$, $p = .0017$). With the exception of the absence of an interaction between distractor location and response condition for the before-target fixations in Experiment 2, this is the same pattern of results as that observed when including the distractor-location repetition trials.