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Post-capture processes contribute to statistical learning of distractor locations in visual search



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ABSTRACT

People can learn to ignore salient distractors that occur frequently at particular locations, making them interfere less with task performance. This effect has been attributed to learnt suppression of the likely distractor locations at a pre-selective stage of attentional-priority computation. However, rather than distractors at frequent (*vs* rare) locations being just less likely to capture attention, attention may possibly also be disengaged faster from such distractors – a post-selective contribution to their reduced interference. Eye-movement studies confirm that learnt suppression, evidenced by a reduced rate of oculomotor capture by distractors at frequent locations, is a major factor, whereas the evidence is mixed with regard to a role of rapid disengagement. However, methodological choices in these studies limited conclusions as to the contribution of a post-capture effect. Using an adjusted design, here we positively establish the rapid-disengagement effect, while corroborating the oculomotor-capture effect. Moreover, we examine distractor-location learning effects not only for distractors defined in a different visual dimension to the search target, but also for distractors defined within the same dimension, which are known to cause particularly strong interference and probability-cueing effects. Here, we show that both oculomotor-capture and disengagement dynamics contribute to this pattern. Additionally, on distractor-absent trials, the slowed responses to targets at frequent distractor locations—that we observe only in same-, but not different-, dimension conditions—arise pre-selectively, in prolonged latencies of the very first saccade. This supports the idea that learnt suppression is implemented at a different level of priority computation with same-versus different-dimension distractors.

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1. Introduction

When scanning our visual environment, we are usually guided by expectancies, such as those deriving from the context of a scene (e.g., [Võ et al., 2019](#)). For instance, we expect the soap to be on the sink (rather than the floor) because soap and sink are related to each other through a common action context and we have learned that the soap is usually found on the sink. Thus, our search behavior is driven not only by semantic but also by statistical properties of the searched-for target objects. That observers can make use of such statistical regularities has also been demonstrated in laboratory visual search tasks: without being explicitly told, after some repetitions, observers find search targets faster at locations where they appeared more frequently ([Druker & Anderson, 2010](#); [Fecteau et al., 2009](#); [Geng & Behrmann, 2001, 2005](#)). This (implicit) learning of uneven distributions of target locations has been referred to as *probability-cueing effect*: the most probable target location is ‘cued’ by the target having appeared there more often compared to other locations. This effect also manifests in oculomotor behavior: eye movements are more likely to land on the target when it appears at a frequent location compared to other locations in the display ([Walthev & Gilchrist, 2006](#)).

More recent studies have demonstrated that observers can similarly learn statistical regularities pertaining to task-irrelevant, but highly salient distractor stimuli: such distractors cause less interference (i.e., delay the response to the target less) when they appear at locations at which they occur more frequently over the course of trials—from which it has been concluded that statistically frequent distractor locations can be better inhibited at some pre-selective level of processing, reducing their power to capture attention (e.g., [Di Caro et al., 2019](#); [Ferrante et al., 2018](#); [Wang & Theeuwes, 2018a, 2018b](#)). This finding holds also for entire regions of the search display encompassing multiple locations, rather than just specific distractor locations ([Goschy et al., 2014](#); [Liesefeld & Müller, 2020a](#); [Sauter et al., 2018, 2019](#)).

While there is a consensus that distractor-location probability cueing modulates the attentional (selection) priority of associated distractor locations, two important open issues concern at what level in the hierarchical architecture of priority computation the suppression effect is implemented: invariably at the level of the attention-guiding (overall-) priority map ([Ferrante et al., 2018](#); [Wang & Theeuwes, 2018a, 2018b](#)), or, depending on how the irrelevant distractor is defined relative to the target, a dimension-specific level of saliency computation below the priority map (e.g., [Sauter et al., 2018](#); [Sauter et al., 2019](#)) and (ii) whether the interference reduction in response times (RTs) brought about by distractor-location learning originates exclusively at a pre-selective level (i.e., prevention of attentional capture) or whether post-selective processes (e.g., post-capture disengagement of attention), too, contribute to the reduced interference. Evidence in favor of a pre-selective origin of statistical distractor-location learning was recently reported by two eye-movement studies ([Di Caro et al., 2019](#); [Wang et al., 2019](#)) which both found reduced oculomotor capture by salient distractors at likely versus unlikely (distractor) locations.

However, the evidence was inconclusive as regards a post-capture effect: expedited disengagement of the eye from distractors at frequent versus rare locations. Furthermore, neither of the two studies systematically varied the way the distractor was defined relative to the target: in a different dimension (e.g., orientation-defined target, color-defined distractor) versus the same dimension (orientation-defined target, orientation-defined distractor). According to the *dimension-weighting account* (DWA; e.g., ([Found & Müller, 1996](#); [Müller et al., 2009](#)); for recent reviews, see [Liesefeld et al., 2018](#), and [Liesefeld & Müller, 2019](#), [Liesefeld et al., 2020b](#)), the dimensional relationship is crucial for the level of learnt distractor inhibition: the priority map with same-dimension distractors versus a saliency map specific to the distractor dimension with different-dimension distractors ([Liesefeld & Müller, 2020a](#); [Sauter et al., 2018, 2019](#)). Thus, it remains unclear whether the pre- and post-selective processing dynamics would be the same with the two types of distractor.

Here, we set out to tackle both issues by implementing an eye-movement study of statistical distractor-location learning which avoided some of the problems that limited conclusions from the prior studies as to the contribution of post-capture processes to interference reduction and which compared and contrasted a condition with different-dimension distractors with one with same-dimension distractors.—In order to set the stage, we review the crucial findings pertaining to the two issues in turn.

1.1. Issue 1: the role of pre-selective and post-selective processes in statistical distractor-location learning

Virtually all studies of statistical distractor-location learning assumed that suppression of the likely distractor location(s) operates on a pre-selective stage of priority computation, modulating the attention-capturing power of distractors at the frequent versus the rare locations, whether at a dimensional or the priority-map level ([Di Caro et al., 2019](#); [Ferrante et al., 2018](#); [Goschy et al., 2014](#); [Sauter et al., 2018, 2019](#); [Wang & Theeuwes, 2018a, 2018b](#)). However, this is not the only feasible explanation for the distractor-location probability-cueing effect. Observers might (additionally) learn, at a post-selective stage, to quickly disengage attention from distractors at the frequent location(s), while being relatively slow in disengaging from a distractor at the rare locations ([Fukuda & Vogel, 2010](#)). Such rapid disengagement is assumed to be controlled by top-down processes that act only relatively late, after bottom-up-driven selection of the distractor ([Born et al., 2011](#); [Godijn & Theeuwes, 2002](#); [Mulckhuyse et al., 2009](#); [Schreij et al., 2010](#); [Theeuwes, 2010](#); [Theeuwes et al., 2003](#)).

In particular, rejection of distractors and, consequently, disengagement of attention might be expedited at the frequent distractor location ([Geng & DiQuattro, 2010](#)), and/or selection of responses to targets at this location might be slowed ([Huang et al., 2004](#)). For instance, assume that what observers learn in distractor-location probability-cueing paradigms is a decision bias toward an item occurring at the likely distractor location being a distractor and against it being a target. In terms of a drift-diffusion model ([Ratcliff & McKoon, 2008](#)), the starting point of evidence accumulation might be shifted toward the distractor boundary and away from the

target boundary. This would generate both a distractor-location effect (faster disengagement from distractors at frequent vs rare locations), and, on the flipside, a target-location effect (slower responses to targets at the frequent vs rare locations). This alternative account could at least in part explain why (virtually all) studies of statistical distractor-location learning have observed a distractor-location effect (reduced interference by distractors at frequent locations), while some studies have observed this to be coupled with a target-location effect (prolonged RTs to the target at frequent locations on distractor-absent trials), at least under some conditions.

Given the close links between the oculomotor and attentional systems (e.g., Deubel & Schneider, 1996; Kowler et al., 1995), one way to dissociate pre- and post-selective processes of distractor handling involves examining the eye-movement dynamics in the search task, over and above the final manual RTs. That is, would statistical learning of distractor locations result in a reduced rate of oculomotor capture by distractors at frequent versus rare distractor locations (indicated by fewer first saccades landing on the distractor), consistent with pre-selective, ‘attentional-suppression’ accounts? And/or would it be reflected in faster disengagement of the eye from distractors at frequent versus rare locations (indicated by reduced fixational dwelling on distractors at frequent locations) and thus faster redirection to the target, consistent with a post-selective, ‘attentional-disengagement’ account? The evidence from two recent eye-movement studies is mixed: Wang et al. (2019) found both a reduced rate of oculomotor capture by a distractor appearing at the frequent location and a slightly reduced dwell time on such a distractor, compared to distractors at the rare locations. Di Caro et al. (2019), by contrast, only found reduced capture, without faster disengagement.

However, besides providing inconsistent results regarding the (non-)existence of a post-selective effect of statistical distractor-location learning (there was agreement regarding a pre-selective effect), we contend that specifics of the paradigms implemented in the two studies actually prevented a definite assessment of this question. In more detail, implementing a variation of Theeuwes (1991) ‘additional-singleton’ paradigm with a shape-defined target and a color-defined distractor singleton, Wang et al. (2019) made one specific location more likely to contain a distractor compared to all other locations (exactly as in Wang & Theeuwes, 2018a; 2018b). As, on distractor-present trials (2/3 of the trials), the shape-defined target never occurred at the location of the color-defined distractor, making one location likely to contain a distractor necessarily meant that it was unlikely to contain a target. Thus, finding a rapid-disengagement effect, Wang et al. (2019) could not rule out that, in their words, the reduced fixation duration on a distractor at the likely location was owing to “observers learn[ing] that the target was less likely to appear at [that] ... location” (p. 1818)—rather than, or in addition to, learning that the distractor was more likely to appear at that location. For instance, observers might learn to bias post-selective, focal-attentional stimulus (distractor/target) discrimination at this location away from a target and towards a distractor decision (See also Zhang et al., 2019, for a potential role of

statistical target-location learning in the Wang-&-Theeuwes, 2018a, 2018b, paradigm.).

In contrast to Wang et al. (2019), Di Caro et al. (2019)¹ presented distractors exclusively at task-irrelevant locations. In more detail, distractors—which were defined by both an abrupt onset and a unique (red) color—appeared at locations in-between an array of potentially relevant locations, consisting of green nontargets and a gray target singleton; this array was preceded by a placeholder array of uniform gray stimuli, which, upon search display (and distractor) onset, changed into green items, except for the single target item that remained gray. Thus, the spatial coordinates of *all* distractors (whether denoting likely or unlikely locations) were impossible target locations, and this division of potential target from distractor locations could have maximized disengagement speed, thereby obviating any faster disengagement of the eye from likely, as compared to unlikely, distractor locations. This leaves open the possibility that faster disengagement from likely distractor locations (e.g., due to an acquired post-selective decision bias) becomes measurable only if the locations at which distractors are presented are also potential target locations.

Thus, to overcome these limitations of the two prior studies on oculomotor effects in distractor probability cueing and decide whether post-selective processes do play a role in statistical distractor-location learning, in the present experiment we adopted the ‘region-cuing’ paradigm of Goschy et al. (2014) and Sauter et al. (2018; 2019). Importantly, this paradigm (illustrated in Fig. 1) features a fully overlapping set of target and distractor locations in that the target appears with equal probability at any *potential* distractor location in both the frequent and the rare distractor region without ever appearing at the *current* distractor location (on distractor-present trials). This way, a disengagement effect may come to the fore—as, in contrast to Di Caro et al. (2019) distractors appear at possible target locations; but it cannot be attributed to learning of the target location—as, in contrast to Wang et al. (2019), there is no target-location bias that could be learnt.

1.2. Issue 2: differential oculomotor capture and disengagement dynamics for same- and different-dimension distractors

Of note, in both prior eye-movement studies, the distractor stood out in a different feature dimension than the target (in Wang et al., 2019, the distractor was color-defined and the target shape-defined; in Di Caro et al., 2019, the distractor was onset- [as well as, redundantly, color-] defined, and the target was color-defined). However, we have repeatedly shown that distractors (solely) defined in the same dimension as the target cause greater overall interference than different-dimension distractors even if matched for bottom-up saliency (e.g., Liesefeld et al., 2017; Liesefeld et al., 2019; Liesefeld & Müller, 2019). This is consistent with the DWA, according to which distractor (saliency) signals arising in a different dimension to the target can be efficiently handled by reducing

¹ It should be noted that although the Di Caro et al. (2019) study bears on the question of a post-selective, rapid-disengagement effect, it was not specifically designed to address it.

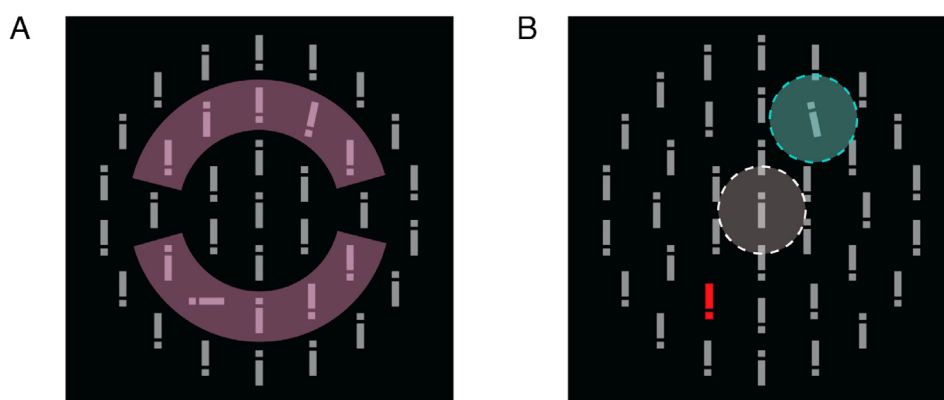


Fig. 1 – Example of a stimulus display for the same-dimension condition (A) and the different-dimension condition (B). In both panels, the search target is the 12°-tilted bar at the 1 o'clock position (on the intermediate circle), the distractor is located at the 7 o'clock position. Pink areas (in A) indicate the top and bottom semicircles used as frequent (vs rare) distractor areas. White and turquoise areas (in B) depict the fixation boundary prior to search display onset and the saccade landing boundary around the search target, respectively. Note that colored areas are for illustration purposes only and were not shown to the observers in the experiment. Figure retrieved from Sauter et al., 2020, available under CC-BY-4.0.

the weights of all signals from this dimension prior to their integration by the (supra-dimensional) priority map. However, with distractors defined in the same dimension as the target, this strategy would not be available (or, at least, be non-optimal), because globally down-weighting all saliency signals from this dimension would reduce not only the selection priority of the distractor (and thus potential to cause interference), but also that of the target, hampering selection of the task-critical item. Thus, same-dimension distractors cause overall greater interference than different-dimension distractors and so provide a greater incentive for statistical distractor-location learning, evidenced by larger probability-cueing effects (e.g., Liesefeld & Müller, 2020a; Sauter et al., 2018; Sauter et al., 2019). Accordingly, the relative contributions of pre- and post-selective processes to the RT cueing effect may be better discernible, and so be best examined with, with same-dimension distractors.

Critically, based on our previous RT work (Liesefeld & Müller, 2020a; Sauter et al., 2018, 2019) and in line with the DWA, we proposed that with different-dimension distractors, learnt inhibition of locations in the frequent distractor region is implemented at a different level of pre-selective priority computation compared with same-dimension distractors (orientation-defined target, color-defined distractor). One crucial (purely RT-based) finding underpinning this proposal was that when target and distractor stood out within the same dimension (orientation-defined target, orientation-defined distractors), processing of the target was impaired, too, when it appeared in the frequent distractor region—suggesting that, in this case, the reduced interference effect was due to suppression of all singletons within a given display region, whatever their specific features. By contrast, target processing was not impaired for singleton distractors defined in a different dimension to the target (orientation target, color distractor).²

Critical evidence for this dissociation comes from a combined RT and modeling study by Liesefeld and Müller (2020a). Using a similar design to Sauter et al. (2018; 2019), randomized trial displays could contain either a same- or a different-dimension distractor, but only one type of distractor occurred more often in one versus the other display region (whereas the other type appeared equally often in both regions), so that there could be learning of an unequal distribution only for this 'biased' type of distractor. When a distractor defined in the same dimension as the target (orientation) was spatially biased, the processing of signals from both the target and the other, spatially unbiased distractor defined in a different dimension (luminance) were likewise reduced in the 'frequent' region. We took this to indicate that constraining spatial suppression to a specific distractor feature is not possible, and participants instead resort to purely space-based (distractor-feature-independent) suppression at the supra-dimensional priority map. In contrast, when the different-dimension (luminance) distractor was spatially biased, processing of other objects in the 'frequent' region, whether target or same-dimension distractor, was entirely unaffected (as supported by strong evidence in terms of Bayes factors, $BF_{10S} < .18$)—indicative of suppression being implemented at a subordinate, dimension-specific level of priority computation. The postulation of such a level, in-between the entry-level feature maps and the attention-guiding priority map, sets the DWA apart from other accounts of attentional selection (see Liesefeld et al., 2018, and Liesefeld & Müller, 2019, for reviews).

However, although the dissociative effect pattern in Sauter et al. (2018, 2019)—that is, statistical learning affecting both the processing of the distractor (reduced distractor interference) and that of the target (slowed processing of the target) with same dimension distractors, but only the processing of the distractor with different-dimension distractors—is consistent with distractor suppression being implemented at different levels of pre-selective priority computation, previous studies could not rule out that the target-location effect with same-dimension distractors arises at a post-selective (rather

² For conflicting findings, see Ferrante et al. (2018) and Wang and Theeuwes (2018a,b); for a reconciliation of the discrepant findings, see Zhang et al. (2019).

than a pre-selective) level. To elaborate, post-selective target/distractor analysis of any item that attracted attention would be expected to be generally harder, and so take more time, when distractors are defined within the same dimension as the target as compared to a different dimension; for example, establishing that the selected item has a different tilt to the response-critical target (as in Sauter et al.'s same-dimension condition) would be harder than simply establishing that it has the wrong color (different-dimension condition). Assuming in addition that post-selective target/distractor discrimination is biased towards a 'distractor' and thus away from a 'target' decision for any selected item in the frequent (vs the rare) distractor region, this could give rise to a target-location effect especially when target/distractor discrimination is hard, that is: in the same-dimension condition. For instance, if the starting point of the evidence accumulation process is shifted towards a 'distractor' decision as a result of statistical learning, it would take more time for evidence to reach the 'target' boundary. Thus, based on the pure RT measure recorded by Sauter et al. (2018, 2019), one cannot conclusively tell whether the target-location effect observed with same-dimension distractors arises at a pre-selective or at a post-selective processing level, or whether it involves contributions from both levels.

1.3. Rationale

Given this, in the present study, we compared and contrasted a different-dimension and a same-dimension distractor condition in order to examine for dissociations in oculomotor—in addition to RT—variables between the two types of distractors. We further aimed to decide whether the target-location effect, which is seen exclusively with same-dimension distractors, originates at a pre-selective level, and/or at a post-selective level. This issue is of significance for the DWA because we have proposed that the target-location effect reflects a modulation (suppression) at the level of the attention-guiding, pre-selective priority map. Accordingly, with a spatially biased same-dimension distractor (but not with a different-dimension distractor), we expected the first saccade to the target on distractor-absent trials (on which the target is the only singleton item in the display) to be influenced by whether it appears in the frequent or the rare distractor region. Given that variation in priority (saliency)—in the present study as a result of statistical distractor-location learning—does not only affect the likelihood of (covert or overt) attention allocation but also its speed (Töllner et al., 2011; van Zoest & Donk, 2005), the predicted oculomotor target-location effect would be expressed in either a reduced proportion of first saccades directed to targets in the frequent (vs the rare) distractor region, or a prolonged latency of such saccades, or both.

2. Methods

2.1. Transparency and openness statement

We report how we determined our sample size by means of theoretical comparison and report a power analysis, all data

exclusions in pre-processing, subsequent analyses, and all data inclusion/exclusion criteria. We did not exclude any participants. All trial-based inclusion/exclusion criteria were established prior to data analysis. We report all data manipulations in the study. The study and/or analysis plan were not preregistered. The experiment and analysis code, as well as the anonymized data are available on OSF: https://osf.io/k9prw/?view_only=42fd0ab5741a4559b210eda6b97e3a93 (peer-review link).

2.2. Participants

Forty-eight observers (28 females and 20 males, ages 18–35 years), recruited from participant panels at Ludwig-Maximilians-University (LMU) Munich, took part in the study, 24 in the different-dimension distractor condition and 24 in the same-dimension condition. In the present study, we were interested in the (within-subject) effects of statistical learning of likely distractor locations for same- and different-dimension distractors. To ensure we have the power to resolve these basic effects, we performed a power analysis based on the effect sizes observed in comparable studies. In these, the distractor-location effect was only about one third the size with different-as compared to same-dimension distractors, with the former also producing much lower standardized effect sizes. Given this, sample size was determined based on the weaker *different-dimension-distractor* effect. Most similar to the present design are Experiment 1 of Goschy et al. (2014; $d_z = 1.18$) and Experiment 1 of Sauter et al. (2019; $d_z = 1.01$). To be on the safe side, we based our power calculations on the latter, smaller effect size. With $\alpha = .05$ and $1 - \beta = .95$, an a-priori power analysis (G*Power 3.1.9.2, Faul et al., 2014) for a directed, paired t test resulted in a minimal sample size of $n = 15$. Concerning comparisons across distractor types, we had found a difference in the probability-cueing effect between same- and different-dimension distractors before (Sauter et al., 2019; $d = 2.17$). A power calculation for an unpaired t test yielded a minimal total sample size of $n = 20$. Finally, to resolve also slightly weaker (compared to those mentioned above) novel within-subject effects, we ran an additional power analysis ($\alpha = .05$ and $1 - \beta = .80$) for an effect size of $d_z = .6$ that resulted in a sample size of $n = 24$.

All participants reported normal or corrected-to-normal vision; accurate color vision was assured by means of a 10-plate color test (Ishihara, 1918). Participants gave prior informed consent and were naive to the purpose of the experiment. They received 9 € per hour in compensation. The study was approved by the ethics committee of the LMU Faculty of Psychology and Education and conducted in accordance with the Declaration of Helsinki.

2.3. Apparatus

The experiment was conducted in a sound-attenuated, moderately lit test chamber. The search displays were presented at a viewing distance of 60 cm on a 21-in SONY GDM-F500R CRT screen (Tokyo, Japan), with a spatial resolution of 1024 by 768 pixels and a vertical refresh rate of 120 Hz. The dominant eye's gaze position was recorded using an SR Research EyeLink 1000 Desktop Mount eye tracker (Osgoode,

Ontario, Canada), at a sampling rate of 1 kHz. Observers issued their responses using a standard keyboard by pressing the “x” or “m” key with their left- or right-hand index finger, respectively. The experimental software controlling display presentation, response collection, and eye-tracking was implemented in Matlab (MathWorks, Natick, MA, USA), using the Psychophysics (Brainard, 1997; Pelli, 1997) and EyeLink toolboxes (Cornelissen et al., 2002), running on an Apple iMac Intel Core i5 computer (Cupertino, CA, USA).

2.4. Stimuli

The search displays were presented on a black background and consisted of one singleton (orientation-defined) target presented amongst 36 other items: either 36 non-targets or 35 non-targets plus one singleton distractor. Item centers were equidistantly arranged on three imaginary concentric circles with radii of 3 dva (degrees of visual angle), 6 dva, and 9 dva, comprising of 6, 12, and 18 bars, respectively. A further bar occupied the position in the center of the three circles. All bars were 2.025 dva in height and .375 dva in width and had a .188 dva wide gap randomly located .375 dva from the top or the bottom of the bar.

Non-targets consisted of gray (RGB: 127, 127, 127; CIE [Yxy]: 49.8, .31, .31), vertically oriented bars. The singleton target differed from these by being tilted 12° either clockwise or counterclockwise (orientation randomly selected for each trial). Note that amongst vertical non-targets, 12° tilted targets produce reliable ‘pop-out’, evidenced by a flat search RT/set size function with a slope near 0 msec/item (Liesefeld et al., 2016), indicative of very ‘efficient’ search.

In 50% of the trials, randomly intermixed, one of the non-targets was replaced by a singleton distractor. Depending on the distractor condition (randomly assigned to each participant), this distractor differed from the non-targets either in the same dimension as the target, being tilted 90° from the vertical (orientation: same-dimension distractor), or in a different dimension, namely, by being colored red (RGB: 255, 15, 15; CIE [Yxy]: 39.5, .54, .34; color: different-dimension distractor). Note that singleton eccentricity was held constant, that is, the singleton target and (if present) the singleton distractor appeared only on the intermediate circle (6 dva radius). All remaining non-target stimuli served to equate local feature contrast amongst the various singleton positions (Bravo & Nakayama, 1992; Nothdurft, 1993).

Note that, in a ‘baseline’ experiment, the (here less distracting) different-dimension color distractor was established to be equally or even more salient than the same-dimension orientation distractor (Zehetleitner et al., 2013). In this experiment, six observers (who did not later take part in the main experiment) performed three target-search conditions in counterbalanced order: search for a red (color-defined) singleton (corresponding to the distractor in the different-dimension condition); search for a horizontal (orientation-defined) singleton (corresponding to the distractor in the different-dimension condition); and search for a 12°-tilted (orientation-defined) singleton (corresponding to the target in both the different- and same-dimension conditions). Note that the displays with 12°-tilted targets were identical to the target displays presented in the main experiment, except that they

never contained a second, irrelevant singleton. Results revealed that a similar proportion of first saccades was directed to the red and the horizontal target, 92% versus 90%, [$t(9.88) = .76, p = .464, d_z = .44, 95\% \text{ CI } [-.10, .05]$], but a numerically smaller portion to the 12°-tilted target, 81%, [red vs 12°-tilted: $t(7.54) = 2.3, p = .052, d_z = 1.33, 95\% \text{ CI } [-.00, .22]$, horizontal vs 12°-tilted: $t(8.05) = 1.73, p = .122, d_z = 1, 95\% \text{ CI } [-.03, .20]$]. Latencies of the first saccade were somewhat shorter for the red compared to both the horizontal target, 166 msec vs 184 msec, $t(8.06) = -2.93, p = .019, d_z = 1.69, 95\% \text{ CI } [4 \text{ msec}, 32 \text{ msec}]$ and the 12°-tilted target, 166 msec vs 196 msec, ($t(8.15) = -4.97, p = .001, d_z = 2.87, 95\% \text{ CI } [-44 \text{ msec}, -16 \text{ msec}]$), and numerically shorter for the horizontal than for the 12°-tilted target, 184 msec vs 196 msec [$t(10) = -1.63, p = .134, d_z = .94, 95\% \text{ CI } [-28 \text{ msec}, 4 \text{ msec}]$]. Thus, taking the two measures together: if anything, the physical saliency of the red singleton was higher than that of the horizontal singleton, and both had a higher saliency compared to the 12° singleton.

2.5. Design

The type of distractor (same-vs different-dimension) was manipulated as a between-subject factor, with each 24 observers randomly assigned to the same- and the different-dimension condition. We chose to implement distractor type as a between-subject factor to ensure that statistical learning of the spatial distractor distribution was specific to a given type of distractor, avoiding sequence effects (i.e., carry-over of, or interference with, learning) when the same observers perform both conditions one after the other. In addition to the distractor condition, the frequency distribution of the singleton distractor across the top and bottom halves of the search display was manipulated as a between-subject factor, with the top half ranging from the 10 o'clock to the 2 o'clock position (top semicircle) and the bottom half from the 4 o'clock to the 8 o'clock position (bottom semicircle) (see Fig. 1A). For half of the participants, the top semicircle was the frequent distractor area; for the other half, the bottom semicircle was the frequent area. Targets and distractors were located only at positions on the intermediate circle, except for the 3 o'clock and 9 o'clock positions as these could not be unambiguously assigned to the frequent or rare area.

A distractor was present in a random 50% of the trials per block. If present, the distractor appeared in the frequent area approximately 90% of the time (‘frequent distractor’) and in the rare area approximately 10% of the time (‘rare distractor’). The target appeared with equal probability in both areas, at any of the 10 possible positions, but it never appeared at the same position as the distractor. For example, assume the distractor occurs at position 1 (of 5 possible positions) in the frequent region. So, while the target will appear with a probability of 50% in the frequent region in general, it cannot be placed at position 1, but it can be presented at any of the other possible positions 2, 3, 4, and 5 in the frequent region. In this way, by randomly allocating the target to one of these positions, we can ensure that the target occurs equally often (at each position) in the frequent as in the rare region. The order of trials within each block was randomized. The experiment consisted of 1000 trials in total, subdivided into 10 blocks of 100 trials each.

2.6. Procedure

The experimental procedure was similar to that of Sauter et al. (2018), while display and item dimensions were scaled to encourage eye-movement execution (as ensured in pre-tests). Observers' task was to discern whether the target bar was interrupted (by a gap) at the top versus the bottom. If it was interrupted at the bottom, they had to press the "x" key; if it was interrupted at the top, they had to press the "m" key. Observers were informed that on some trials, there would be a horizontal (same-dimension condition) or, respectively, a red (different-dimension condition) distractor bar, which they should ignore as it would be irrelevant to their task. Observers were not informed that the distractor would be more likely to appear in one particular (semicircular) display region.

Each trial started once stable fixation was detected within a (virtual) circular region (radius: 2.5°) centered on a white (fixation) cross (radius: .2°, width: .04°) presented in the middle of the screen. After a random duration between 700 msec and 1100 msec, the search display appeared. Observers were instructed to make an eye movement to the target and indicate the gap position in the target bar via a keyboard-button press; they were told to do so as fast and as accurately as possible. The search display was presented until a response was given. If the response was incorrect, the word "ERROR" appeared in the center of the screen for 500 msec. If participants gave their response before performing any eye movement or if they did not make any eye movement at all (i.e., the eye did not leave a virtual circle of 2.5 dva around the fixation cross; see Fig. 1B), the message "YOU NEED TO LOOK" was displayed for 1000 msec. Such trials (on average 5.21 trials for the whole experiment, i.e., 52% of all trials presented) were repeated in random order at the end of each block. The next trial started with the reappearance of the central fixation cross. After each block of trials, observers received feedback on their average RT and accuracy and were free to take a short break before resuming the experiment.

To establish whether they had gained any explicit knowledge of the singleton distractors' spatial frequency distribution, participants filled in a brief questionnaire after completing the experiment in which they were asked whether the distractor had appeared more often on a specific semi-circle (4 response alternatives: top, left, bottom, right). Of note, only 17 of the 48 observers (35%) indicated the correct semicircle.

2.7. Eye-data pre-processing

The recorded eye-position data were analyzed off-line, and saccades were identified based on their velocity distribution using a moving average over twenty successive eye-position samples (Engbert & Mergenthaler, 2006). Saccade onset and offset were determined when the velocity exceeded or fell below the median of the moving average by 3 SDs for at least 20 msec. Trials were included in the analyses if correct fixation was maintained within 2.5 dva from the fixation cross prior to search display onset and if at least one saccade was made outside of this boundary before a key press response was given. A saccade was marked as landing on the target or the distractor if its endpoint was within 2.5 dva from the

respective item center (see Fig. 1B). Trials with a (manual) response error (4.3%) were excluded from all analyses and 99.48% of all correct-response trials were included in the eye-movement analysis.

3. Results

3.1. Response times

Fig. 2 depicts the group mean response times (RTs; group means based on median RTs per participant) as a function of the distractor condition (distractor absent, distractor in frequent region, distractor in rare region), separately for the two types of distractor (same-dimension, different-dimension).

For same-dimension distractors, RTs were slower when a distractor was present than when it was absent (721 msec vs 627 msec); $t(23) = 12.89$, $p < .001$, $d_z = 2.63$, 95% CI [79 msec, 109 msec]. There was also a marked distractor-location (probability-cueing) effect: RTs were faster when distractors were located in the frequent compared to the rare distractor region (709 vs 818 msec), $M = -109$ msec; $t(23) = -11.17$,

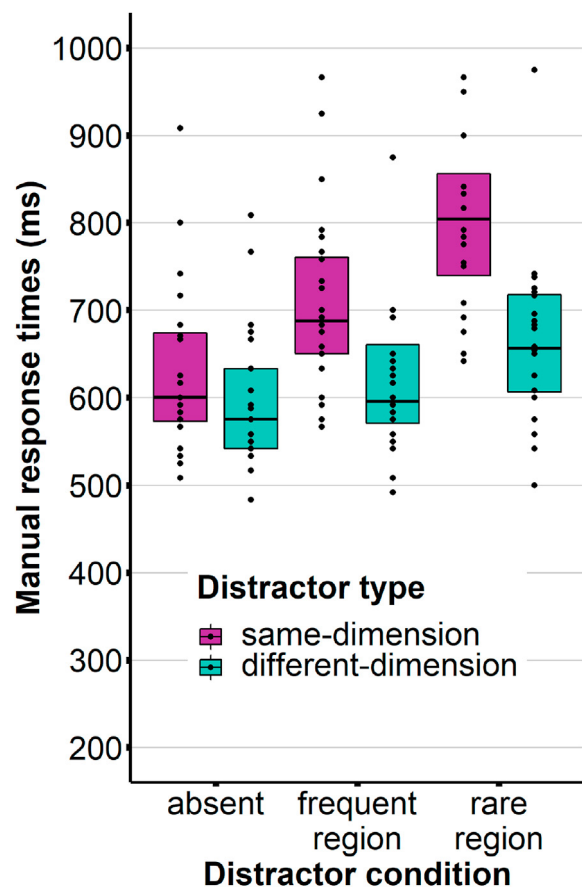


Fig. 2 – Mean response times (calculated from individual participants' medians) as a function of distractor condition (absent, frequent region, rare region) and distractor type (same-dimension vs different-dimension). Colored boxes mark the 25th to 75th percentile range of the group data; black dots show the individual participants' median RTs.

$p < .001$, $d_z = 2.28$, 95% CI [-129 msec, -89 msec]. We also examined for an effect of the target location on RTs on trials without a distractor (which would provide a pure measure of target suppression; see Sauter et al., 2018; Liesefeld & Müller, 2020a, Appendix B). Indeed, replicating our previous findings, targets were responded to slower when they appeared in the frequent versus the rare distractor region (640 vs 614 msec); $M = 24$ msec, $t(23) = 4.19$, $p = .001$, $d_z = .85$, 95% CI [13 msec, 38 msec].

For different-dimension distractors, RTs likewise were slower when a distractor was present than when it was absent (629 msec vs 595 msec); $t(23) = 5.59$, $p < .001$, $d_z = 1.14$, 95% CI [22 msec, 47 msec]. There was also a probability-cueing effect: RTs were faster when distractors appeared in the frequent as compared to the rare distractor region (625 vs 680 msec); $t(23) = -4.97$, $p < .001$, $d_z = 1.01$, 95% CI [-78 msec, -32 msec]. However, on distractor-absent trials, there was no significant RT difference between targets appearing in the frequent and the rare distractor region (604 msec vs 603 msec); $t(23) = .26$, $p = .797$, $d_z = .05$, 95% CI [-7 msec, 9 msec].

Thus, with reference to the no-distractor baseline, distractor interference was substantially greater with same-than with different-dimension distractors (136 msec vs 58 msec), $t(44.56) = 6.12$, $p < .001$, $d = 1.77$, 95% CI [53 msec, 104 msec] (Welch's t -test). The probability cueing effect was also twice as large with same-as compared to different-dimension distractors (109 vs 55 msec), $t(45.26) = 3.65$, $p = .001$, $d = 1.05$, 95% CI [24 msec, 84 msec]. Overall, this is a replication of the effect pattern found by Sauter et al. (2018, 2019) in a design optimized to induce and measure eye movements.

3.2. Eye movements

3.2.1. Landing-position frequency

To some extent, the interference effects reported above (including their modulation by the type of distractor and the biased distractor distribution) may be driven by oculomotor capture by the distractor delaying selection of the response-

relevant target item. Oculomotor capture can be measured in terms of the likelihood with which the first saccade is directed to the distractor, rather than going straight to the target (see Fig. 3). Indeed, compared to the distractor-absent condition, the presence of a distractor significantly reduced the probability with which the first saccade landed on the target, for both distractor-type groups; same-dimension distractors, .79 vs .28, $t(23) = -13.29$, $p < .001$, $d_z = 2.71$, 95% CI [-.59, -.43]; different-dimension distractors, .82 vs .44, $t(23) = -10.54$, $p < .001$, $d_z = 2.15$, 95% CI [-.45, -.30]. The reduction turned out significantly larger with same-than with different-dimension distractors [.50 vs .38; $t(44.57) = 2.14$, $p = .038$, $d_z = .62$, 95% CI [-.01, .20]; Welch's t -test].

Given this, we examined the frequency with which the first saccade landed on the target when the distractor appeared in the frequent versus the rare region, for both distractor types in a joint ANOVA (see Fig. 3A) followed up by direct comparisons. In a 2×2 ANOVA with the factors distractor type (same-dimension vs different-dimension) and distractor location (frequent vs rare region), the main effect of distractor type was significant, $F(1, 46) = 7.5$, $p = .009$, $\eta_p^2 = .14$, the main effect of distractor location was significant, $F(1, 46) = 285.82$, $p < .001$, $\eta_p^2 = .86$ and the interaction distractor type \times distractor location was significant, $F(1, 46) = 6.14$, $p = .017$, $\eta_p^2 = .12$. For both distractor types, initial saccades landed more often on the target when the distractor appeared in the frequent distractor region compared to the rare region: same-dimension, .31 vs .09, $t(23) = 8.38$, $p < .001$, $d_z = 1.71$, 95% CI [.16, .27]; different-dimension, .47 vs .23, $t(23) = 7.51$, $p < .001$, $d_z = 1.53$, 95% CI [.17, .30]. This cueing effect did not differ significantly between same- and different-dimension distractors [.22 vs .24, $t(44.31) = .49$, $p = .629$, $d_z = .14$, 95% CI [.06, -.10]; Welch's t test].

To examine more directly for oculomotor capture, we went on to assess how often the initial saccade was directed at the distractor when it appeared in the frequent versus the rare distractor region (see Fig. 3B). It should be noted that this analysis is essentially an inverse of the former analysis, as the majority of first saccades are directed to either the target or

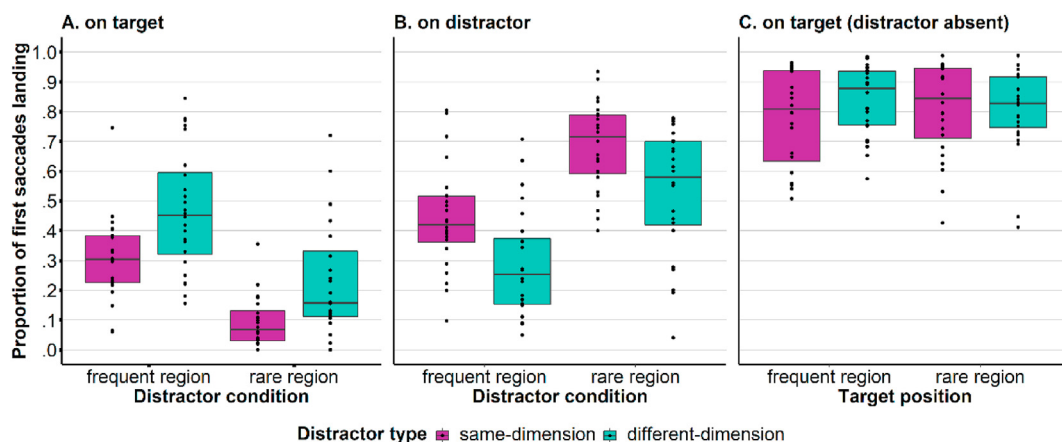


Fig. 3 – Proportions of the initial saccades landing on the target (A & C) or distractor (B) as a function of distractor type (magenta: same-dimension vs teal: different-dimension). Panels A and B show the proportions as a function of distractor location (x-axis; frequent vs rare region). Panel C shows the proportions as a function of the target position (x-axis; frequent vs rare distractor region). Black dots show individual participants' proportions. Colored boxes mark the 25th to 75th percentile range of the group data.

the distractor. However, because there are residual first saccades being directed at (non-salient) non-targets, distractor-directed saccades need to be analyzed separately. In a 2×2 ANOVA with the factors distractor type (same-dimension vs different-dimension) and distractor location (frequent vs rare region), the main effect of distractor type was significant, $F(1, 46) = 11.00$, $p = .002$, $\eta_p^2 = .19$, the main effect of distractor location was significant, $F(1, 46) = 97.44$, $p < .001$, $\eta_p^2 = .68$ and the interaction distractor type \times distractor location was not significant, $F(1, 46) = .00$, $p = .977$, $\eta_p^2 = .00$. Fewer first saccades landed on a distractor appearing in the frequent as compared to the rare region (indicative of suppression). This was the case for both types of distractor: same-dimension, 44% vs 68%; $t(23) = -7.01$, $p < .001$, $d_z = 1.43$, 95% CI $[-.31, -.17]$; different-dimension, 29% vs 53%; $t(23) = -6.95$, $p = .001$, $d_z = 1.42$, 95% CI $[-.32, -.17]$. Again, this cueing effect did not differ significantly between same- and different-dimension distractors: 24% vs 24%, $t(45.99) = .03$, $p = .977$, $d = .01$, 95% CI $[-.10, -.10]$ (Welch's t -test). Finally, we examined the effect of target location, in the frequent versus the rare distractor region, on the direction of first saccades to the target on trials on which the distractor singleton was absent in the display (see Fig. 3C). Distractor-absent trials are particularly suited for this analysis, in that they permit the effect of the distractors' biased distribution on overt attentional orienting to the target to be investigated without potential distortions arising from the actual presence of a distractor (Liesefeld & Müller, 2020b; Appendix B; see also Wang et al., 2019). In a 2×2 ANOVA with the factors distractor type (same-dimension vs different-dimension) and target location (frequent vs rare distractor region), the main effect of distractor type was significant, $F(1, 46) = .56$, $p = .459$, $\eta_p^2 = .01$, the main effect of target location was not significant, $F(1, 46) = .00$, $p = .998$, $\eta_p^2 = .00$ and the

interaction distractor type \times target location was not significant, $F(1, 46) = 2.95$, $p = .092$, $\eta_p^2 = .06$. For same-dimension distractors, the probability of initial saccades towards the target did not significantly differ between the frequent and the rare region, albeit being numerically slightly reduced for the former (78% vs 81%); $t(23) = -1.17$, $p = .252$, $d_z = -.24$, 95% CI $[-.10, .03]$. There was also no significant difference for different-dimension distractors (84% vs 81%); $t(23) = 1.26$, $p = .220$, $d_z = .26$, 95% CI $[-.02, .09]$.

3.2.2. Saccadic latency

Across all trials, first saccades directed to the distractor were initiated faster than first saccades to the target (214 vs 197 msec: $t(93.72) = 4.39$, $p < .001$, $d_z = .90$, 95% CI [9 msec, 24 msec])—mirroring the higher probability of the distractor attracting the first saccade.

To examine for variation in the timing of oculomotor capture by the distractors, we examined the influence of both distractor type (same-, different-dimension) and distractor location (in frequent, rare region) on saccadic latency on trials in which the first eye movement landed on the distractor (see Fig. 4A). Irrespective of distractor location, saccades were initiated slightly slower to same-dimension as compared to different-dimension distractors [204 vs 190 msec: Welch's $t(45.27) = 2.77$, $p = .008$, $d = .8$, 95% CI [4 msec, 23 msec]], consistent with the baseline test in which these distractor stimuli were presented as targets (see Method section above). Importantly, saccades to distractors had slightly longer latencies when the distractor appeared in the frequent as compared to the rare distractor region, with same-dimension distractors [204 msec vs 197 msec: $t(23) = 2.67$, $p = .014$, $d_z = .54$, 95% CI [2 msec, 13 msec]]; although going in the same direction, the difference was not significant with different-

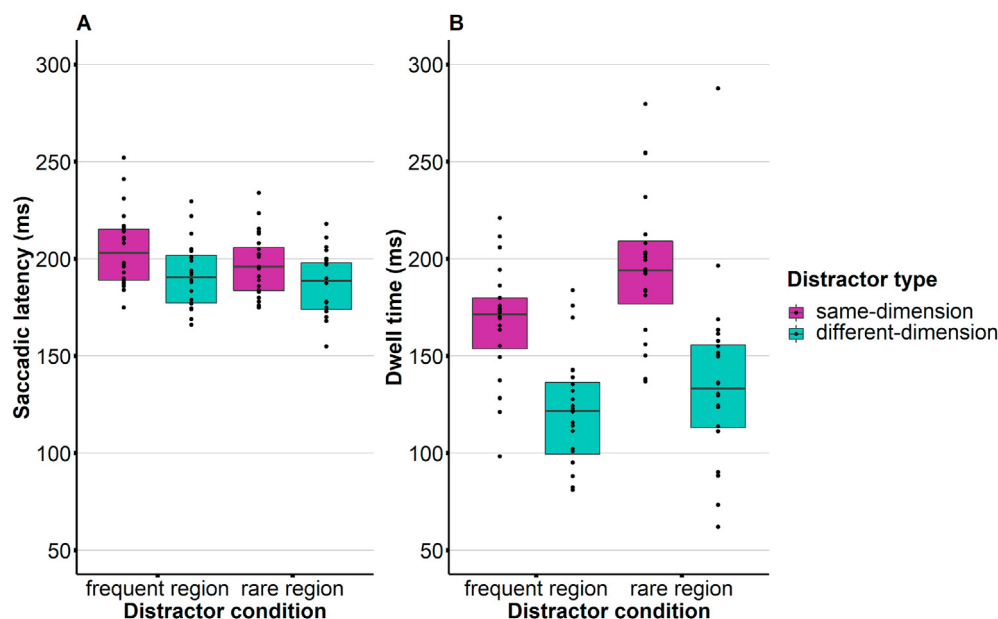


Fig. 4 – Saccadic latencies of initial saccades landing on the distractor (A), and post-saccadic dwell times on the distractors (B), both as a function of distractor location (x-axis; frequent vs rare region) and distractor type (colored; same-dimension vs different-dimension). Black dots show individual participants' means. Colored boxes mark the 25th to 75th percentile range of the group data.

dimension distractors [191 msec vs 187 msec: $t(23) = -1.75$, $p = .093$, $d_z = .36$, 95% CI [-1 msec, 9 msec]].

Finally, we examined for effects of target location on saccadic latency, on distractor-absent trials. Recall that the probabilities of initial saccades directed towards the target in the absence of a competing distractor did not differ between the frequent and the rare region, even with same-dimension distractors. On its own, the absence of a significant target-location effect in the same-dimension-distractor group could be taken to argue against the notion that distractor suppression with this type of distractor is implemented at the priority-map level (impacting target as well as distractor processing). However, if not in the probability, a target-location effect might be evident in the latency of the first saccades directed to the target in the same- (but not the different-) dimension condition. Indeed, on distractor-absent trials, it took participants significantly longer to initiate a saccade towards a target located in the frequent, versus the rare, distractor region when distractors were defined in the same dimension as the target [232 msec vs 217 msec; $t(23) = 4.08$, $p < .001$, $d_z = .83$, 95% CI [8 msec, 24 msec]], but not when they were defined in a different dimension [218 msec vs 211 msec; $t(23) = 1.71$, $p = .101$, $t(23) = 1.95$, $p = .063$, $d_z = .40$, 95% CI [0 msec, 15 msec]]. The difference between the two distractor-type (same-vs different-dimension) groups was not significant, $t(45.78) = 1.65$, $p = .105$, $d = .48$, 95% CI [-2 msec, 20 msec].

To sum up, saccades to distractors were initiated faster compared to saccades to targets, indicative of the former being more salient. Consistent with the baseline study (in which all objects were targets), saccadic latency was longer to same-as compared to different-dimension distractors, suggesting a higher degree of caution (fixational ‘hold’) with distractors that caused greater interference. Further, with same-, but not reliably with different-dimension distractors, saccades were initiated slower to distractors in the frequent as compared to the rare region, reflecting the suppression of the frequent-distractor region. The same was true for saccades to targets on distractor-absent trials, consistent with suppression operating at the level of the priority map under the same-dimension distractor condition.

3.2.3. Ocular dwell times

The above analyses confirm that suppression of the frequent distractor region on a pre-attentive priority map is one mechanism underlying the reduced interference from distractors in the frequent, as compared to the rare, distractor region. To test whether there is a potential for post-selective rapid disengagement playing a role in this effect, we examined the dwell time following capture of the eye by the distractor, that is: the fixation duration after the first saccade landing on the distractor, before the eye went on to the next item, most likely the target (Fig. 4B). Overall, dwell times were longer on same-dimension distractors than on different-dimension distractors (173 vs 123 msec), $t(45.83) = 5.67$, $p < .001$, $d = 1.64$, 95% CI [32 msec, 67 msec] (Welch's t -test). Importantly, in the same-dimension condition, the dwell times were shorter on distractors in the frequent region, compared to distractors in the rare region: 167 vs 200 msec

[i.e., dwell-time savings of 33 msec for frequent-region distractors: $t(23) = 4.29$, $p < .001$, $d_z = .88$, 95% CI [-49 msec, -17 msec]]. Numerical savings (of 15 msec) were also evident with different-dimension distractors (121 vs 136 msec), but they were not significant, $t(23) = -1.96$, $p = .062$, $d_z = .40$, 95% CI [-33 msec, 1 msec]; they did however not differ significantly from those in the same-dimension condition, 33 vs 15 msec; $t(45.90) = 1.54$, $p = .13$, $d = .45$, 95% CI [-5 msec, 40 msec] (Welch's t -test). These savings are indicative of expedited disengagement of the eye from distractors in the frequent (as compared to distractors in the rare) region.

A similar rapid-disengagement effect most likely occurs with different-dimension distractors (in the frequent region), but is hard to demonstrate given the relatively short dwell times in this condition. In contrast to the long dwell times on same-dimension distractors, these short dwell times do not provide much room for a strong effect of distractor region to emerge (probably due to physiological limitations as discussed below) and indeed the observed effect size of $d_z = .40$ was below our targeted minimal effect size of $d_z = .60$. In an earlier study, Liesefeld et al. (2019) found differential patterns in the RT distributions between same- and different-dimension distractors. Given this, we extended this approach to the post-capture dwell times to explore whether a distribution analysis would yield further insights into potential differences in statistical distractor-location learning between the two types of distractor and be more sensitive than the original analysis based on mean dwell times. Since the number of trials per participant was very low for some cells of the design (especially dwell times on rare distractors in the different-dimension condition), we refrained from computing paired mean comparisons and, instead, calculated vincentiles for each condition across all participants. The dwell time distribution (see Fig. 5) reveals that 45% of dwell times are shorter than 100 msec on distractors in the frequent region, as compared to only 28% with fixations on distractors in the rare region. These frequency distributions of ‘above 100 msec’ and ‘below 100 msec’ dwell times are significantly different, $\chi^2(1, N = 1758) = 63.54$, $p < .001$. In summary, the distribution analysis shows that there is an increased fraction of very short dwell times on different-dimension distractors in the frequent region. On these trials, the eye disengaged from the distractor already 50 msec earlier than the time typically deemed to be required for programming and initiating an eye movement (e.g., Findlay, 1997). This is consistent with a (very) rapid-disengagement effect and indicates that programming the saccade away from the distractor may already have started before the eye landed on the distractor.

A shift in the (overall) distribution is also evident for same-dimension distractors. Very short dwell times (<100 msec), however, remain relatively infrequent, even for distractors in the frequent region (rare vs frequent region: 7% vs 16%, $\chi^2(1, N = 5248) = 43.02$, $p < .001$). Instead, the shift manifests largely in the slower (>100-msec) time range (e.g., time bin 100–150 msec: 41% for the frequent region vs 30% for the rare region)—a duration sufficiently long to process the fixated distractor's identity to make a ‘reject and disengage’ decision.

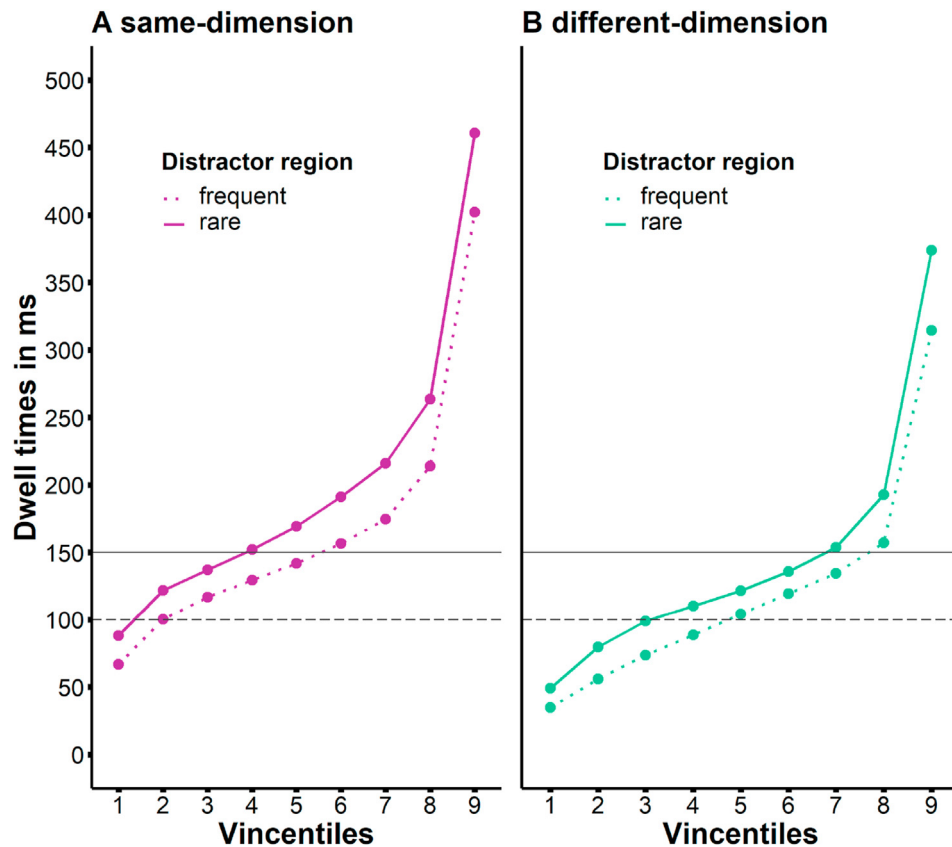


Fig. 5 – Dwell times on same-dimension distractors (A) and different-dimension distractors (B) as a function of their vintiles (binning dwell times in nine equally-sized bins, and then taking the mean for each bin), computed per condition across all participants. A solid horizontal line highlights the cut-off of 150 msec, which has been considered the minimal time it takes to program and initiate a saccade (e.g., Findlay, 1997); the dashed line indicates the cut-off of 100 msec, below which fixations can be considered too short to allow for effective information uptake. As can be seen, for different-dimension distractors, only the slowest dwell times are above 150 msec. There are differences in dwell times between same- and different-dimension distractors even for the shortest dwell times.

4. Discussion

The present study employed eye-tracking to examine the relative contribution of pre- and post-selective processes to effects of statistical learning of likely distractor locations, where the learning is overall evidenced in terms of reduced RT interference by salient distractors that occur in a likely (frequent), as compared to an unlikely (rare), distractor region. In particular, we investigated two interrelated issues. First, as previous evidence was inconclusive, we re-investigated at which processing stages learnt ‘suppression’ of distractors (in a frequent distractor region) exerts its influence: only at the stage of pre-attentive priority computations, preventing capture in the first instance (pro-active suppression; Di Caro et al., 2019), or additionally at the post-capture stage of distractor rejection, expediting attentional disengagement from a task-irrelevant distractor (re-active suppression; Wang et al., 2019). Second, by implementing two conditions with distractors either defined in the same or a different dimension as the target, we examined whether the target-location effect observed on distractor-absent trials in the same-, but not the different-, dimension distractor condition (Sauter et al., 2018,

2019) is already reflected in the first eye movements directed to the target—consistent with a pre-attentive locus of this theoretically important effect.

4.1. Contributions of oculomotor capture and disengagement to distractor-location probability cueing

In terms of the mechanisms underlying the distractor-location probability-cueing effects, the results were clear-cut: statistical learning of the likely distractor region involves pre-selective spatial suppression of this region (consistent with the specific-location paradigms employed by Di Caro et al., 2019, and Wang et al., 2019), as indicated by our analyses of the landing positions and latencies of the first saccades; additionally, it involves faster attentional disengagement from distractors in this region, as indicated by our dwell-time analyses. Positively establishing expedited disengagement under conditions that avoid the drawbacks of the earlier studies is a new finding, evidencing statistical distractor-location learning at a processing stage following oculomotor capture, independently of target-location learning.

Of note, while Di Caro et al. (2019) and Wang et al. (2019) had already shown that suppression at the pre-attentive

priority map does play a significant role, to what extent and under which conditions more rapid post-selective disengagement contributes to producing the pattern of RT effects remained inconclusive. In contrast to these studies, we used a region-cueing paradigm (adapted from Sauter et al., 2018, 2019), which offers two advantages for deciding this question: it permitted the distractor distribution to be manipulated independently of the target distribution (increased likelihood of a distractor occurring in the frequent vs the rare distractor region but equal likelihood of the target appearing at any location), thus precluding any confounding of statistical distractor-location learning by target-location learning; further, the set of possible distractor locations was not distinct from the set of possible target locations, so that distractor locations could not be ruled out as being task-irrelevant.

We go on to discuss these two major effects—oculomotor capture and disengagement—in turn, with a focus on the effect with regard to which the present study goes beyond prior work: oculomotor disengagement.

4.1.1. Prevention of oculomotor capture

Overall, on distractor-present trials, fewer saccades tended to land immediately on the target and more were initially captured by same-as compared to different-dimension distractors (on target: 28% vs 44%; on distractor: 47% vs 31%). Note that even though the different-dimension distractor was somewhat more salient than the same-dimension distractor (as determined in a baseline study), a greater competition for attentional selection between targets and same-dimension distractors was expected based on the DWA (Liesefeld & Müller, 2019; Liesefeld et al., 2018, 2019).

The overall greater interference, or oculomotor-capture, of the same-dimension distractor goes along with a numerically larger distractor-location effect. In particular, with a distractor appearing in the frequent as compared to the rare region, relatively more (24% different-dimension to 22% same-dimension) saccades were directed straight to the target and relatively fewer (24% for both same- and different-dimension distractors) saccades were first mis-allocated to the distractor—indicative of learnt spatial suppression of the frequent distractor region.

Further, saccades to distractors in the frequent distractor region had relatively longer latencies, suggesting that these distractors were slower to summon attention—again consistent with spatial suppression of the frequent distractor region.

4.1.2. Rapid disengagement

The effects discussed thus far are consistent with pro-active spatial suppression of the frequent versus the rare distractor region, in line with Di Caro et al. (2019) and Wang et al. (2019). However, our results also provide clear evidence that differential disengagement processes play a role. Not only were distractors in the frequent region less likely to capture attention, but the ensuing dwell time on these distractors was also 15 msec and 33 msec shorter (in the different- and same-dimension conditions, respectively). This demonstrates the existence of a rapid-disengagement effect, which contributes to the overall RT effect in statistical distractor-location learning (reduced RT with distractors at frequent vs rare locations)—under conditions that avoid the aforementioned

issues with the designs of the previous eye-movement studies. However, as such this effect does not explain why disengagement is faster from distractors in the frequent versus the rare region. There appear to be two (related) possibilities: (i) the post-selective processing time required to identify a distractor as a task-irrelevant item and make a ‘reject’ decision may be shorter for distractors in the frequent as compared to the rare region. The post-selective identification of an attended item may involve a two-alternative drift-diffusion process (e.g., Ratcliff & McKoon, 2008), with the boundaries corresponding to a ‘distractor’ and a ‘target’ decision; for each display location, the starting point of evidence accumulation is set according to the learnt likelihood of this location containing a distractor versus a target. Accordingly, the starting point would be shifted closer to the ‘distractor’ boundary for frequent as compared to rare distractor locations, shortening the time required to identify the distractor. (ii) Alternatively, or additionally, distractor rejection may require a re-active suppression of the priority signal generated by the distractor below the level of the signal generated by the target (which is likely to be the next most salient item) so that attention can be disengaged from the distractor in order to be shifted to the target item (Liesefeld et al., 2017; Liesefeld & Müller, 2020a). Given distractors occurring at frequent, as compared to rare, locations generate weaker priority signals (because frequent locations are pro-actively suppressed), re-active suppression and release of attention might take less time for distractors at frequent as compared to rare locations.

4.1.3. Comparisons to prior work

Our finding of a disengagement effect contrasts with Di Caro et al. (2019), who furthermore observed extremely short average dwell times (90 msec vs 93 msec for distractors at frequent versus rare locations; personal communication, June 7, 2019). This may be due to a specific feature of their paradigm: as the set of possible distractor locations was distinct from the set of possible target locations, distractors capturing the eye could be quickly ruled out as potential target solely based on their spatial coordinates. Two features of Di Caro et al. (2019) findings are consistent with this possibility: (i) In their study, the oculomotor capture effect (measured in terms of the reduced proportion of first saccades going to the target on distractor-absent vs -present trials or the proportion going straight to the distractor on distractor-present trials, averaged across locations) was overall relatively weak and the cueing effect (the differential capture effect between the frequent and rare locations) was thus weak as well: ~20% and ~10%, respectively. This diminished cueing effect may have made it hard to resolve a disengagement effect. (ii) Even if a distractor (whether at a frequent or a rare location) did capture the eye, the ensuing fixation duration was so short that hardly any analysis of the fixated item could have been performed. Presumably little analysis was necessary anyway, as the attentional control system would have been quickly able to realize that the eye had saccaded (or was about to saccade) to an “impossible” target location (the likelihood of a distractor location containing a target was zero, so the post-selective identification process would have been massively biased towards a ‘distractor’ decision), immediately setting in motion a ‘corrective saccade’ to the next most salient item. In fact, this

saccade may already have been prepared in parallel with the execution of the distractor-directed saccade.

By contrast, in the present study, the capture and cueing effects in the comparable different-dimension condition were relatively large (53% and 29%, respectively) and targets could occur at distractor locations. This presumably lessened the bias towards a ‘distractor’ decision in post-selective stimulus identification and permitted a disengagement effect to come to the fore. Recall, however, that this effect was mainly driven by saccades with very short dwell-times: the percentage of dwell times shorter than 100 msec was significantly increased for distractors in the frequent versus the rare region. As with Di Caro et al. (2019), this suggests that, with different-dimension distractors, no or little post-saccadic stimulus analysis was necessary especially when the eyes were captured by a distractor in the frequent region—likely because the distractor was identified as such and consequently rejected already while initiation of the first saccade progressed beyond the ‘point of no return’, that is: the corrective saccade was programmed in parallel with the first saccade (see also Becker et al., 2009; Findlay, 1997; Theeuwes, 2004). This would imply that what looks like a ‘disengagement’ effect reflects, at least in part, a failure to immediately update the oculomotor program upon determining that the current saccade goal is not the target (see also Gabbay et al., 2019).

Before comparing our results to Wang et al. (2019), it is instructive to consider several aspects of their data. Their on-distractor dwell times were relatively long (151 vs 174 msec for distractors at frequent vs rare locations), that is, some 164 msec on average, which compares with ~90 msec in Di Caro et al. (2019) and ~120 msec in the present different-dimension condition. Generally, dwell times of this length are consistent with post-saccadic checking of the fixated distractor stimulus to ascertain its status as a task-irrelevant, to-be-rejected item. The need for such close checking may particularly arise in Wang et al. (2019) paradigm because of the random swapping of the color assigned to the distractor and the non-distractor (including the target) items, as a result of which the distractor and the target were non-predictably green or red on different trials (in contrast, the distractor color was fixed in Di Caro et al., 2019, and the present different-dimension condition). From ‘priming of pop-out’ paradigms (e.g., Maljkovic & Nakayama, 1994), it is known that on color-swap trials the eye is often misdirected first to a non-target item possessing the same color as the target on the previous trial, rather than being directed straight to the singleton color target (Becker, 2008; Caddigan & Lleras, 2010).

³ In Wang et al. (2019), only relatively few first saccades went straight to the target in the absence of a distractor (some 35%, i.e., considerably less than the >85% in Di Caro et al. and the present study)—indicating that the target itself provided little guidance. As a result, the eye movements may have been distributed fairly ‘erratically’, including many saccades to non-target locations. Thus, when a distractor did appear in the display, it drew a high proportion of these non-selective (non-target-directed) saccades as well as some portion of the target-directed saccades. Measured in terms of ‘first-saccades-to-the-distractor’, the capture effect, of 25%, was relatively weak (more in line with the 20% in Di Caro et al. than the 53% for different-dimension distractors in the rare region in the present study).

If the color swapping invokes a similar tendency in Wang et al. (2019) paradigm, this could explain their relatively low rates of first target and distractor fixations (i.e., many first saccades would have been directed to non-targets³), while also explaining the general need for extended scrutiny of the first item that captured the eye.

Wang et al. (2019) did find a significant rapid-disengagement effect of some 25 msec, despite a relatively weak capture effect (see Footnote ³). Recall, however, that in their paradigm the target was less likely to appear at the frequent distractor location; although this was the case only on distractor-present trials, it ‘biased’ the overall spatial distribution of target items. Accordingly, their rapid-disengagement effect might reflect the outcome of two sources of bias in post-selective item examination: a bias in favor of a distractor decision (increased likelihood of a distractor occurring at the frequent location) combined with a bias against a target decision (reduced likelihood of a target occurring at the frequent location), with the latter effectively shifting the starting point of the evidence-accumulation process even further towards the ‘distractor’ boundary. As a result, if there is a distractor at the frequent distractor location, the ‘distractor’ decision is expedited, while minimizing false identifications of the distractor as a target. The reverse would happen on distractor-absent trials on which a target occurs at the frequent distractor location. In this case, ‘target’ evidence would be slow to reach the ‘target’ boundary (due to the increased distance of the starting point from the boundary), while ‘distractor’ evidence may spuriously win the competition (due to the small distance of the starting point from the boundary)—resulting in mistaken disengagement of attention from the target based on a false ‘distractor’ decision and continued search until the target is eventually found.

Seemingly paradoxically, this fast erroneous ‘distractor’ decision would predict a rapid-disengagement effect not only from a distractor at the frequent location (on distractor-present trials), but also from a target (on distractor-absent trials). And this is, in fact, what Wang et al. (2019) found: with a 50 msec shorter dwell time on a target at the frequent versus a rare distractor location, this disengagement effect was even larger than the distractor effect (~25 msec).⁴ In other words, the target at the frequent location tended to be misidentified as a distractor upon attracting the first eye movement, so that the eye would have moved elsewhere before eventually returning to the target, leading to the final response decision (see also Zhaoping, 2012, who reported such erroneous rejections of targets that had captured the eye in a pop-out search task without salient distractors). In the present study, by contrast, the target appeared with equal likelihood in the frequent and the rare distractor region even on distractor-present trials—so participants could not have learned a bias in the target locations. The more rapid disengagement from distractors in the frequent region we observed thus cannot be attributable to such a bias. In fact, in contrast to Wang et al. (2019), we found little difference in the dwell times on the target (on distractor-absent trials) depending on

⁴ Although Wang et al. (2019) report this result (see their section “Attentional dwell time” and Fig. 4C), they do not comment on it.

whether it appeared in the frequent versus the rare distractor region (same-dimension condition: ~ 5 msec; different-dimension condition: ~ 7 msec; both p 's $> .10$).

Thus, with regard to our different-dimension distractor condition (which is comparable to the distractor definition in Di Caro et al., 2019, and Wang et al., 2019), we conclude that rapid disengagement of the eye from frequent distractor locations is a genuine contributor to the probability-cueing effect. However, given the absence of a bias in the spatial target distribution and given the ease of identifying a distractor as such (namely, simply by its invariant color) to make a 'reject' decision, it would appear unlikely that a shift in post-selective decision parameters (along the lines of account (i) above) is a major source of the distractor-location effect on dwell times with our different-dimension distractors. In fact, it appears that here the 'reject' decision may already be made in a 'covert-capture' state, that is, even before an overt eye movement is nevertheless executed to the distractor location—as the re-active suppression of the distractor's priority signal (along the lines of account (ii) above) came too late to prevent oculomotor capture. Nevertheless, even if such oculomotor capture occurred, disengagement is achieved faster from a distractor in the frequent versus the rare region because, due to pro-active suppression of this region, the strength of its priority signal would be lower, which shortens the time required to re-actively reduce its 'saccadic hold' and release the eye to move on to the next most salient item, the target (in line with account (ii) above).

In comparison with the different-dimension condition, our same-dimension distractors produced a larger disengagement effect, with on-distractor dwell times generally shifted into a range consistent with post-saccadic analysis of the fixated item. The latter would be expected given that discriminating a 45° tilted distractor from a 12° tilted target bar (i.e., establishing a quantitative difference) is harder than telling the distractor apart from the target simply by its consistent color (a qualitative difference). In the former condition, having learned that a distractor occurs likely in one region (and unlikely in the other) might induce a bias towards a 'distractor' (90° tilt) and against a 'target' (12° tilt) decision (decision variable: degree of tilt in target dimension), which may play less of a role (if any) when the distractor can be told apart from the target by a unique feature in another dimension (decision feature: unique color in distractor dimension). Accordingly, with same-dimension distractors, more rapid disengagement from a distractor in the frequent versus the rare region might reflect a learnt adjustment of post-selective 'distractor' decisions (e.g., a relative shift of the starting point of evidence accumulation towards the 'distractor' boundary), along the lines of account (i) above.⁵

⁵ This would also mean that the target-location effect on distractor-absent trials is attributable to such a post-selective bias: even though the target summons attention and the eye immediately, it would take somewhat longer for evidence to accumulate to the 'target' boundary for a target located in the frequent (vs one in the rare) region. Of note, however, this account conflicts with our evidence that this target-location effect is purely pre-attentive in nature (see discussion of target-location effects below).

Alternatively, same-dimension distractors generate stronger priority signals than different-dimension distractors (even with equated bottom-up saliency; see also Liesefeld et al., 2019; Liesefeld & Müller, 2020a)—and, the higher the strength of the priority signal, the stronger the 'hold' on attention and the longer it takes to re-direct the eye to the target location. Given that the effect of learnt suppression (of the frequent as compared to the rare distractor region) is also greater with same-than with different-dimension distractors, there would be a greater difference in the time required to build down the attentional 'hold' signal and redirect the eye to the target, from a distractor in the frequent region versus one in the rare region (in line with account (ii) above). The resulting rapid-suppression effect could combine with any effect arising from a bias in the 'distractor'-versus-'target' decision.

Further work (involving modeling of the disengagement dynamics) would be required to clarify how these two post-selective processes—identification of an item as a distractor and re-active suppression of its priority signal—interact. Also, rather than being discrete, additive stages, they may be (partially) overlapping in time, that is: a certain level of 'distractor' evidence below the boundary may already suffice to tell the 'disengage' system to start re-active suppression, perhaps with the strength of suppression scaled according to the level of accumulated evidence. Further, the distractor priority signal may not need to be nulled completely for attention, and the eye, to be disengaged from the distractor location; rather, it may suffice to reduce the priority of the distractor to some level below that of the target for the latter to be selected. Methodologically, we propose that these issues are best addressed using same-dimension distractor conditions: as these cause more interference to start with (Liesefeld et al., 2017, 2019; Liesefeld & Müller, 2019), their probability-cueing effect is overall larger, and, consequently, subtle effects at different stages of processing can be better resolved—as was also the case in the present study where several effects were highly significant for same-dimension distractors and only approached the significance criterion for different-dimension distractors.

4.2. Target-location effects

Finally, we comment on two issues relating to the DWA, both concerning the differential target-location effects (target in frequent vs rare distractor region) between the same- and different-dimension distractor conditions.

4.2.1. Pre-selective source of the target-location effect with same-dimension distractors

In previous comparable eye-tracking studies (Di Caro et al., 2019; Wang et al., 2019), the distractor was always defined in a different dimension to the target. Based on our previous observations of a target-location effect (i.e., slowed RTs to targets in the frequent vs the rare distractor region on distractor-absent trials) manifesting only with same-, but not different-dimension distractors, we proposed that suppression occurs at different levels of priority computation with the two types of distractors (Liesefeld & Müller, 2020a; Sauter et al., 2018, 2019; Zhang et al., 2019). Accordingly, it was of

theoretical importance to establish that the target-location effect does not simply originate at a different processing stage to the distractor-location effect (specifically, a mere post-selective bias against a ‘target’ decision for frequent distractor locations in the same-dimension condition), but rather that both the distractor- and the target location affect already the very first eye movement (in line with a pre-selective origin of both effects).

We replicated the overall-RT interference effects of our previous studies (Sauter et al., 2018, 2019): interference, relative to the distractor-absent baseline, was reduced for distractors in the frequent versus the rare region (distractor probability-cueing effect), and the interference and the magnitude of the cueing effect were larger with same-than with different-dimension distractors (even though, if anything, the different-dimension distractor was somewhat more salient). Additionally, on distractor-absent trials (i.e., when displays contained no distractor that could elicit interference dynamics), RTs were slowed when the target appeared in the frequent versus the rare region with same-dimension distractors but not with different-dimension distractors—consistent with the notion that spatial statistical learning occurs at different levels in the hierarchical architecture of search guidance: the search-guiding priority map with same-dimension distractors versus the distractor dimension with different-dimension distractors (Liesefeld & Müller, 2020a; Sauter et al., 2018, 2019; Zhang et al., 2019). Analyses of the first eye movements on distractor-absent trials confirmed that this effect is pre-attentive in origin: it took longer to initiate first saccades towards targets in the frequent versus the rare distractor region (along with the probability of such saccades being numerically reduced). That is, the learnt distractor distribution affected the timing of the very first saccade to targets in the frequent region—as well as the timing and probability of the first saccades to distractors on distractor-present trials—indicating that the suppression must be implemented at the level of the attention-guiding pre-attentive priority map. Further analyses, detailed in the Appendix, show that there is no post-selective contribution to this effect.

4.2.2. Target-location effect with different-dimension distractors

Of note, in the different-dimension distractor condition, we found no evidence of a target-location effect on either the RTs or the first saccades to targets located in the frequent region, which is consistent with the proposal that with this type of distractor, suppression is implemented at the level of the distractor dimension (cf. Sauter et al., 2018, 2019). In fact, Liesefeld and Müller (2020a) recently provided strong evidence in terms of Bayes factors and computational modeling that with our design the target-location effect is fully absent with different-dimension distractor learning. At variance with our findings, however, such a target-location effect was evident in the different-dimension paradigm of Wang et al. (2019). As argued by Zhang et al. (2019; see also Allenmark et al., 2019), this discrepant result is likely attributable to specifics of Wang et al.’s paradigm (which was adopted from Wang & Theeuwes, 2018a), in particular: random color swapping between distractor and non-distractor items (including the target) across

trials plus an overall reduced likelihood of a target occurring at the frequent versus one of the rare distractor location(s) (see also the discussion of the rapid-disengagement effect in Wang et al., 2019, above). Zhang et al. (2019) showed that when the color assignment is consistent and when targets occur with equal probability at all (the frequent and rare) item locations (as was also the case in the present experiment), there is no (or at least no persistent) target-location effect on distractor-absent trials with different-dimension distractors.⁶ In other words, in the different-dimension (distractor) condition, suppression of the frequent distractor region leaves processing of the (shape, orientation) target unaffected, consistent with the notion that the suppression operates at the level of the distractor (color) dimension (i.e., in terms of the DWA: ‘down-weighting’ of the distractor dimension; see, e.g., Liesefeld & Müller, 2020a, for a schematic representation see Sauter et al., 2018). By contrast, in the same-dimension (distractor) condition, suppression of the frequent distractor region impedes processing of the (shape, orientation) target, consistent with the notion that the suppression operates at the level of the search-guiding priority map. Strong evidence for the dissociation between these two levels of suppression has been provided recently by Liesefeld and Müller (2020a), who showed that acquisition of a probability-cueing effect with (spatially biased) same-dimension distractors transferred to both the target and another, unbiased, different-dimension distractor. In fact, as demonstrated by computational modeling, all three location effects (biased same-dimension distractor, unbiased target, and unbiased different-dimension distractor) can be parsimoniously explained by a single spatial-weighting parameter implemented in the model. In contrast, probability cueing acquired with different-dimension distractors exhibited no transfer whatsoever to either the target or the same-dimension distractor. That is, when suppression (of a frequent distractor region) is learned at the priority-map level, it impacts the processing of any object, whether it is defined in the same or a different dimension relative to the target. By contrast, when suppression is learned at the dimensional level (in response to a biased different-dimension distractor), it impacts only objects defined in the distractor dimension, but not targets or distractors defined in another dimension.

5. Conclusion

We conclude that next to pre-selective prevention of attentional capture (by means of spatial suppression), post-selective attentional disengagement dynamics play a role in the reduction of interference caused by statistical learning of

⁶ Note that we do not claim that different-dimension (i.e., color) distractors are invariably suppressed by a dimension-based suppression strategy, given that priority-map-based suppression is in principle available as an alternative—albeit, in terms of target processing, costly—strategy. However, even if they start with a priority-map-based suppression strategy (such as when there is random swapping of the distractor with the target color), (most) observers do revert to dimension-based suppression over the course of learning if the conditions favor such a strategy – as shown by Zhang et al. (2019).

likely distractor locations. In fact, interference reduction is influenced by further post-selective processes that operate after the initial oculomotor-capture and disengagement dynamics, as revealed by exploratory analyses that we present in a separate, [Appendix](#) section. Concerning the disengagement effect, we discussed two likely interacting factors that might produce the reduced dwell time (expedited oculomotor disengagement) on distractors in the frequent versus the rare region: a bias in post-selective distractor identification leading to faster ‘reject’ decisions and weaker priority signals (due to pro-active suppression) expediting re-active suppression of the residual priority signal. Furthermore, with same- but not with different-dimension distractors, suppression of the frequent distractor region impacted not only the likelihood of the distractor in this region capturing attention, but also the speed with which a target in this region was initially fixated (target-location effect). Together with previous evidence, this is consistent with the idea that suppression operates at a global, priority-map level in the same-dimension condition (down-weighting all salient signals: distractor but also target signals), whereas it operates at the level of the distractor dimension (down-weighting only distractor signals) in the different-dimension condition (cf. [Liesefeld & Müller, 2020a](#); [Sauter et al., 2018](#); [Sauter et al., 2019](#); [Zhang et al., 2019](#)).

Open practices

The study in this article earned Open Materials, Open Data badges for transparent practices. Materials and data for the study are available at https://osf.io/k9prw/?view_only=42fd0ab5741a4559b210eda6b97e3a93.

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Appendix

Distractor-location probability-cueing effects beyond oculomotor capture and disengagement

The eye-movement results presented in the main article indicate that both oculomotor capture and post-capture disengagement contribute to the distractor-location probability-cueing effect on RTs, certainly with same-dimension distractors and potentially also with different-dimension distractors. However, there may be further, as yet unexplored processes, beyond the oculomotor capture and disengagement dynamics, that are influenced by distractor-location probability cueing. Neither the study of [Di Caro et al. \(2019\)](#) nor that of [Wang et al. \(2019\)](#) did examine for such processes. Given this, in more exploratory analyses, we also looked for distractor-location effects (i) on RTs on trials in which oculomotor capture was successfully prevented (thus ruling out oculomotor capture and disengagement [as

opposed to *attentional* capture and disengagement] as sources of potential distractor-location effects) and (ii) on the time between the saccade away from the distractor (i.e., after disengagement) and the key-press response.

Results

- (i) Besides interfering by capturing attention or the eye, distractors are also known to produce non-spatial filtering costs ([Folk & Remington, 1998](#); [Wykowska & Schubö, 2011](#)). Non-spatial filtering costs and/or covert attentional capture might also be reduced for distractors in the frequent as compared to the rare region. Indeed, when only looking at trials without oculomotor capture (i.e., trials on which the first saccade was not directed to the distractor), there is still a significant RT benefit when the distractor occurs in the frequent region, as compared to the rare distractor region, both for same-dimension distractors (673 msec vs 770 msec; $t(23) = -5.3$, $p < .001$, $d_z = 1.08$, 95% CI [-135 msec, -59 msec]) and for different-dimension distractors (609 msec vs 647 msec; $t(23) = -2.81$, $p = .01$, $d_z = .57$, 95% CI [-66 msec, -10 msec])—with the benefit being larger for same-dimension distractors: 97 msec vs 38 msec; $t(42.41) = 2.58$, $p = .013$, $d = .75$, 95% CI [13 msec, 105 msec] (undirected Welch's test).
- (ii) Following oculomotor capture, distractors might continue to exert an influence even after the eye has disengaged from them—for instance, by engendering more careful target scrutiny—and this influence might also be modulated by probability cueing. To look at this, we examined the time between oculomotor disengagement (onset of the second saccade) and the manual key-press response on trials on which the first saccade went to the distractor. For same-dimension distractors, the time to response turned out significantly shorter when the distractor occurred in the frequent, as compared to the rare, region for same-dimension distractors: 390 msec vs 434 msec; $t(23) = -7.63$, $p < .001$, $d_z = 1.56$, 95% CI [-56 msec, -32 msec]). For different-dimension distractors, the (numerical) benefit was not significant: 362 msec vs 379 msec; $t(23) = -1.48$, $p = .152$, $d_z = .3$, 95% CI [-41 msec, 7 msec]) and in any case smaller than the benefit in the same-dimension condition: 44 msec vs 17 msec vs 44 msec; $t(33.93) = -2.1$, $p = .043$, $d = .61$, 95% CI [1 msec, 53 msec] (undirected Welch's test).

Of note, this effect pattern was associated with the presence of a (same-dimension) distractor in the display: on distractor-absent trials, the time from the target fixation to the manual response did not differ between targets located in the frequent versus the rare distractor region in the same-dimension condition, 368 msec vs 367 msec, [$t(23) = .28$, $p = .783$, $d_z = .06$, 95% CI [-9 msec, 12 msec]]. In the different-dimension condition an effect was numerically present, but not significant, 344 msec vs 352 msec [$t(23) = -1.82$, $p = .081$, $d_z = .37$, 95% CI [-17 msec, 1 msec]]. That there is no target-location effect following oculomotor target selection indicates that the target-location effect for same-dimension

distractor learning (nonsignificant in the rate, but significant in the latency of first saccades, as well as in the manual RTs) is purely pre-attentive in nature.

Discussion

Thus, in addition to oculomotor capture and disengagement effects, we identified two further contributions to the RT probability-cueing effect:

- (i) RTs were faster with distractors occurring in the frequent as compared to the rare region even in trials without oculomotor capture, in particular in the same-dimension distractor condition (in which the benefit was 2–3 times larger than in the different-dimension condition: 97 msec vs 38 msec). This effect might be explained either by covert capture (and subsequent disengagement) of attention happening less often with distractors in the frequent region, or by non-spatial filtering costs (Folk & Remington, 1998; Wykowska & Schubö, 2011) being reduced for the frequent region. Given the small number of trials available for this analysis, it is hard to decide between these two alternatives. Analyzing RTs as a function of the separation of the target from the distractor revealed evidence of a distance effect at least with same-dimension distractors: RTs were slower to targets closer to the distractor⁷—which is taken to be diagnostic of attentional capture (Hickey & Theeuwes, 2011; Koch et al., 2013). However, since we had to ignore the factor ‘distractor region’ for this analysis (due to insufficient trials), we cannot rule out that the distance effect is larger with distractors in the rare versus the frequent region. In other words, it remains possible that distractors in the frequent region are more associated with non-spatial filtering costs, while distractors in the rare region cause more attentional capture. This would need to be established in future work.
- (ii) When oculomotor capture had happened and disengagement of the eye from the distractor was completed, the time from the onset of the target-directed saccade to the response was shorter with distractors in the frequent as compared to the rare region (significantly in the same-dimension condition and numerically in the different-dimension condition: benefit of 44 msec vs 17 msec). This effect is likely to reflect differential reactive adjustment of decision processes on oculomotor-capture trials: Once capture by and identification of a distractor happened, this may slow the processing of the next most salient item selected (the target), more so when the distractor occurred at an unexpected (rare) as compared to an expected (frequent) location. Given that the distractor in the same-dimension condition was a horizontally oriented ‘i’, the orientation of the dot on the distractor ‘i’ (left or

right) was unlikely to interfere with the decision on the target ‘i’ (top vs bottom). Accordingly, it is more likely that the slowing originated at the stage of identifying the second selected item as the target (target/non-target decision; see discussion of the rapid-disengagement effect above). However, exactly which decision parameter (the boundary separation or the rate of evidence accumulation) is changed as a result of the preceding capture event remains to be established in future work.

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⁷ Distractor type \times target-to-distractor distance ANOVA: main effect distractor type: $F(1, 46) = 5.23$, $p = .027$, $p\text{-}\eta^2 = .1$; main effect of distance: $F(5, 230) = 44.27$, $p < .001$, $p\text{-}\eta^2 = .49$; interaction: $F(5, 230) = 17.1$, $p < .001$, $p\text{-}\eta^2 = .27$.

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