



# Region-based shielding of visual search from salient distractors: Target detection is impaired with same- but not different-dimension distractors

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## Abstract

Shielding visual search against interference from salient distractors becomes more efficient over time for display regions where distractors appear more frequently, rather than only rarely Goschy, Bakos, Müller, & Zehetleitner (*Frontiers in Psychology* 5: 1195, 2014). We hypothesized that the locus of this learned distractor probability-cueing effect depends on the dimensional relationship of the to-be-inhibited distractor relative to the to-be-attended target. If the distractor and target are defined in different visual dimensions (e.g., a color-defined distractor and orientation-defined target, as in Goschy et al. (*Frontiers in Psychology* 5: 1195, 2014), distractors may be efficiently suppressed by down-weighting the feature contrast signals in the distractor-defining dimension Zehetleitner, Goschy, & Müller (*Journal of Experimental Psychology: Human Perception and Performance* 38: 941–957, 2012), with stronger down-weighting being applied to the frequent- than to the rare-distractor region. However, given dimensionally coupled feature contrast signal weighting (cf. Müller J, Heller & Ziegler (*Perception & Psychophysics* 57:1–17, 1995), this dimension-(down-)weighting strategy would not be effective when the target and the distractors are defined within the same dimension. In this case, suppression may operate differently: by inhibiting the entire frequent-distractor region on the search-guiding master saliency map. The downside of inhibition at this level is that, although it reduces distractor interference in the inhibited (frequent-distractor) region, it also impairs target processing in that region—even when no distractor is actually present in the display. This predicted *qualitative* difference between same- and different-dimension distractors was confirmed in the present study (with 184 participants), thus furthering our understanding of the functional architecture of search guidance, especially regarding the mechanisms involved in shielding search from the interference of distractors that consistently occur in certain display regions.

**Keywords** Visual search · Perceptual learning · Attentional capture · Location probability cueing · Location suppression · Dimension weighting

When we look for a unique target object within a rich visual scene, often other objects stand out from the background of nontarget items and may capture attention before the target is

attended. In such visual *pop-out* search tasks, observers become more efficient, over time, in minimizing the interference generated by such salient but task-irrelevant distractors when these consistently occur in certain regions of the search display (Goschy, Bakos, Müller, & Zehetleitner, 2014). However, the mechanisms underlying this learning effect, termed *probability cueing of distractor locations* (Goschy et al., 2014), are poorly understood: Do observers learn to suppress distractors on the basis of their likely location alone? Or does space-based suppression combine with feature- or dimension-based suppression mechanisms in some circumstances? In addition, when there are no effective means of object-based suppression, does space-based suppression become so strong that it affects processing of the search target (counter to the intention) as well as of the distractor? These questions were addressed in

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the present study. Before developing these questions and considering in detail how probability cueing of distractor locations may work, we review some key notions concerning the functional architecture underlying the competition of unique, *singleton* target and distractor objects in otherwise homogeneous search arrays.

## Modulation of interference in involuntary attentional capture

Attentional capture by task-irrelevant objects is usually investigated using variants of the *additional-singleton paradigm* (Theeuwes, 1992; see Yantis, 1996, 2000, for discussion). Although the search display consists of one (task-relevant) singleton-feature target amongst homogeneous nontargets, some or all of the displays include an additional (task-irrelevant) singleton-feature distractor. Typically, the additional singleton is more salient than the target—frequently, as in Theeuwes (1992), the target is defined by a unique shape (e.g., a diamond among circles) and the distractor by a unique color (e.g., a red circle among green shapes)—so that, generally, it is highly likely to capture the observer’s attention before the target is selected, thereby prolonging reaction times. Such attentional shifts are considered involuntary because they interfere with the task of producing a speeded response to the target.

This interference of salient additional-singleton distractors can be reduced in some situations (e.g., Gaspelin, Leonhard, & Luck, 2015, 2017; Leber & Egeth, 2006a, b; Müller, Geyer, Zehetleitner, & Krummenacher, 2009). Additionally, Zehetleitner, Goschy, and Müller (2012) showed that the interference reduction does not critically depend on the *search mode* (cf. Bacon & Egeth, 1994) adopted by observers (whether *feature* or *singleton search mode*), but on distractor practice (see also Vatterott & Vecera, 2012, and Gaspelin & Luck, *in press*, for the role of practice in reducing distractor interference). This indicates that observers can acquire some efficient strategy to suppress color-defined distractors when searching for a shape- (or orientation-)defined target. But exactly how this exclusion of distractors is implemented in the functional architecture of search guidance remains unclear.

One clue to answering this question has been provided by Liesefeld, Liesefeld, Töllner, and Müller (2017). Instead of a color-defined distractor, both their distractor and target were defined by orientation: the (less salient) target was defined by a 12° tilt from the vertical, and the (more salient) distractor by a 45° tilt in the opposite direction from the target. Using these stimuli, Liesefeld et al. (2017) observed massive and persistent distractor interference (of 225 ms) over a lengthy electroencephalographic (EEG) experiment. They found no evidence that

observers could reduce the attentional capture by the singleton distractor. Rather, the distractors attracted spatial attention—as evidenced by a distractor N2pc wave, a negative EEG deflection at posterior electrodes contralateral to the distractor. Generally, the N2pc is taken to reflect the allocation of attention to an object in the search display (e.g., Eimer, 1996; Luck & Hillyard, 1994; Töllner, Rangelov, & Müller, 2012; Woodman & Luck, 1999, 2003). Crucially, the distractor N2pc was elicited prior to a shift of attention to the target, as evidenced by a delayed target N2pc. Such a signature pattern of successive distractor- and target-related N2pc waves had never been consistently demonstrated before. A reason for this might be that previous studies focusing on the N2pc had typically used shape-defined targets and color-defined distractors, making it easy to selectively up-weight the target and/or down-weight the distractor signals (Burra & Kerzel, 2013; Hickey, McDonald, & Theeuwes, 2006; Jannati, Gaspar, & McDonald, 2013; Kiss, Grubert, Petersen, & Eimer, 2012; Wykowska & Schubö, 2011; among the exceptions have been studies in which both targets and distractors were defined in the color dimension, which we will consider further in the Discussion section).

## The role of dimension weighting in involuntary attentional capture

Thus, it would appear that when searching for an orientation- (or shape-)defined target, the interference caused by a salient singleton distractor can be effectively reduced when the distractor is color-defined (i.e., when it is a *different-dimension* distractor), but not when it is also orientation- (or shape-)defined (i.e., when it is a *same-dimension* distractor). In fact, this pattern is predicted by the *dimension-weighting account* (DWA) developed by Müller and colleagues (e.g., Found & Müller, 1996; Krummenacher, Müller, Zehetleiter, & Geyer, 2009; Müller, Heller, & Ziegler, 1995; Müller, Reimann, & Krummenacher, 2003). In essence, DWA is a variation of the *Guided Search* model (e.g., Wolfe, 1994, 2007), which assumes that the allocation of focal attention to items in visual search is based on a preattentively computed spatial priority map (henceforth referred to as the *master saliency map*): Items achieving the highest overall saliency are attended with priority. The saliency that items take on in this map depends on their feature contrast to other items in their local surround, within all pertinent feature dimensions (e.g., color and orientation contrast). Additionally, this contrast can be top-down enhanced for features that define the searched-for target, and possibly also reduced for task-irrelevant features—where the down-weighting of specific

features would correspond to *first-order feature suppression*, in the terminology recently introduced by Gaspelin and Luck (in press). The feature contrast signals thus computed are then integrated across dimensions on the master saliency map and subsequently drive spatial selection. At the heart of DWA (and the critical difference from the original Guided Search model) is the notion that this integration operates in a dimensionally weighted fashion (in contrast to simple saliency summation models, such as Guided Search, which assume nonweighted integration, and to models assuming only feature-specific weighting). All feature contrast signals from specific dimensions may be assigned a greater or a lesser influence on guiding the allocation of attention than all feature contrast signals from other dimensions. This down-weighting of all feature contrast signals from one dimension would, in a sense, be similar to second-order feature suppression in Gaspelin and Luck's (in press) terminology (i.e., to suppression of a *feature discontinuity* on a specific feature dimension—e.g., a color discontinuity—without affecting feature discontinuities in other dimensions, such as shape or orientation). Accordingly, according to the DWA, nonspatial visual selection is primarily dimension-based, rather than feature-based, without denying an element of feature-based selection (see the Discussion for further details).

### Role of dimension weighting in the probability cueing of distractor locations

The present study was designed to examine whether the functional architecture envisaged by DWA (see above) can also help us understand how the probability cueing of distractor locations is mediated. Besides the processes of location-independent attentional selection discussed above, search performance is greatly influenced by the spatial distribution of targets and distractors in the search array. It is well-established that observers can learn to exploit uneven distributions of target locations in order to facilitate search: Targets are detected faster at locations where they appear more frequently (e.g., Anderson & Druker, 2010; Fecteau, Korjoukov, & Roelfsema, 2009; Geng & Behrmann, 2002, 2005), which Geng and Behrmann (2002) termed a *target location probability-cueing effect*. Similarly, observers can learn to exploit the statistical distribution of task-irrelevant distractors to improve performance: Over time, they become better at suppressing locations where distractors appear frequently (e.g., Kelley & Yantis, 2009; Leber, Gwinn, Hong, & O'Toole, 2016; Reder, Weber, Shang, & Vanyukov, 2003). Note, though, that the relevant demonstrations have been limited to sparse visual displays that contained only a

few target and distractor stimuli with a very limited number of possible distractor locations.<sup>1</sup> Goschy et al. (2014) showed that distractor location probability learning does generalize from single, specific locations to entire regions of dense search displays. They presented a slightly tilted gray target bar (i.e., an orientation-singleton) among 36 vertical gray nontarget bars. In half of the search arrays, one of the vertical nontargets was red, serving as a highly salient color-defined (i.e., different-dimension) distractor. When present, distractors appeared with 90% probability in one half of the display (the frequent-distractor region) and with 10% in the other half (rare-distractor region). Goschy et al. (2014) found that the distractor captured less attention when it occurred in the frequent than when it appeared in the rare region. This result suggests that (at least with different-dimension distractors) we can exploit uneven spatial distractor distributions to facilitate search performance. However, it remains unclear exactly how this suppression is implemented, and whether it works in the same way with same- as with different-dimension distractors.

### Rationale of the present study

In principle, there are three possibilities for how spatial shielding from distractor interference may work: spatially selective suppression at (1) the global, master saliency level; (2) the specific feature level; or (3) the dimensional level.

**Master-map-based suppression** One possibility is that the reduced interference from distractors in the frequent-distractor region is due to a global bias against the allocation of spatial attention to this region. In terms of search architecture, this would be implemented at the level of the search-guiding master saliency map of the search array (in Gaspelin & Luck's, in press, terminology, this is similar to *global-saliency suppression*; note, though, that Gaspelin & Luck took this to refer to suppression being reactively applied to the most salient item on the global saliency map, rather than to anticipatory suppression of a whole region). Suppression at this level

<sup>1</sup> Reder et al. (2003) used a variation of the *negative-priming* paradigm (adapted from Tipper, Brehaut, & Driver, 1990): The displays consisted of one target and one distractor, with four possible locations, one of which was most likely to contain a distractor. In Kelley and Yantis (2009), the task-relevant red–green dot pattern consistently appeared in the display center, and a distractor (composed of the same colors) could appear at one of two, equally likely peripheral locations. Leber et al. (2016) used a variation of the *contingent-capture* paradigm (e.g., Folk, Remington, & Johnston, 1992): There were four display locations/items (arranged in the form of a square), with the distractor display preceding the target display; distractors (which were singled out from the background stimuli by the same feature as the target: the color red) were most likely to appear at one location, defined by a fixed relationship with the likely target location that was indicated by a central arrow at the start of a trial.

entails that if the frequent-distractor region was inhibited on the master saliency map, the processing of search targets appearing in this spatially suppressed region should be impaired, too. This impairment should even be evident on trials in which no distractor was present, because learned, persistent global suppression of the frequent-distractor region would operate on all trials, whether or not a distractor appeared. Additionally, it would occur independent of whether the distractor was defined in the same dimension as the target or in a different dimension.

**Feature-based suppression** Alternatively, spatial shielding might operate at a level below the search-guiding master saliency map, at which features and feature contrast signals are computed, which would then be integrated into the master saliency map. Distractor suppression could operate on the feature map, down-modulating the distractor-defining feature directly (in Goschy et al., 2014: the feature “red”), with stronger down-modulation being applied to the frequent than to the rare region. This is essentially a spatially selective version of first-order feature suppression (cf. Gaspelin & Luck, *in press*). Suppressing distractor feature signals in the frequent-distractor region (more than in the rare region) would attenuate their weight when transferred to the corresponding locations on the master saliency map, making them less competitive for the allocation of focal attention. If such a direct feature weighting is the general mechanism by which shielding works, it would predict *no* impairment of processing for targets in the frequent relative to the rare-distractor region, whether the distractor were defined in the same dimension as the target or in a different dimension (since in both cases, only the distractor feature would be suppressed).

**Dimension-based suppression** Alternatively, as is assumed by the DWA, spatial shielding could operate on the dimension-specific feature contrast map, down-modulating the strength of any feature contrast signals in the dimension in which the distractor is singled out from the nontargets (in Goschy et al., 2014: the dimension “color”), more so for the frequent than for the rare region. This is essentially a spatially selective version of second-order feature suppression (cf. Gaspelin & Luck, *in press*). Accordingly, a dissociation would be expected between conditions with distractors defined in the same dimension as the target versus in a different dimension (cf. Müller et al., 2009; Zehetleitner et al., 2012): Impairment of target processing in the frequent as compared to the rare-distractor region would *not* be expected when the distractor was defined in a different dimension to the target, in which case any signals from the distractor dimension could be suppressed without impacting signals from the target dimension. But impairment would be expected if the distractor were defined within the

same dimension as the target: In this case, because of dimensional coupling, applying dimension-based suppression would impact target as well as distractor signals.<sup>2</sup>

Based on the DWA, our working hypothesis was as follows: Probability cueing (i.e., effectively stronger suppression applied to the frequent than to the rare-distractor region) operates at the dimension-specific level when distractors are defined in a different dimension from the target—leaving target processing unaffected. But when distractors are defined within the same dimension as the target, space-based shielding operates (if it can operate at all) at either the dimension-specific level or the level of the master map; both would be associated with a cost (i.e., a cost additive to any distractor probability-cueing effect) for target processing in the frequent as compared to the rare region.

We tested this hypothesis by comparing and contrasting the effects of same-dimension and different-dimension distractors. Distractor type was manipulated between subjects (i.e., in separate experiments).<sup>3</sup> Specifically, we examined (1) whether a distractor probability-cueing effect would also be observed with same-dimension distractors (rather than only with different-dimension distractors); (2) whether adaptation to the unequal distractor distribution (i.e., frequent- vs. rare-distractor region) would also impact target processing; and (3) whether any such impact would qualitatively differ between the same- and different-dimension distractor conditions.

To isolate pure distractor location probability-cueing effects, the data needed to be cleaned of short-term intertrial repetition effects and effects of the distance between the target and the distractor in the search array, both of which can influence visual search and both of which may differ between the frequent- and rare-distractor regions. How we dealt with these two types of potential confounds and what impact they had on actual search performance is described in detail in the [Appendix](#). Note that eliminating potentially confounding trials is costly in terms of the number of trials, or participants, required. We opted for recruiting a larger sample of

<sup>2</sup> An alternative strategy to dimension-based suppression (which might be deemed counterproductive, since the target can be detected only on the basis of signals in the single critical dimension) might be to resort to inhibition at the level of the master saliency map. But this would again lower the response of saliency units to the target (as well as to the distractor) in the frequent (suppressed) region—in line with global spatial shielding (see above). Accordingly, with same-dimension distractors, a target location effect (slowed responding to targets within the frequent vs. the rare distractor region) would be expected in both cases.

<sup>3</sup> The aim of the study was to examine focal hypotheses regarding the effects of target position (dependent on the type of distractor) in distractor probability cueing. These hypotheses were *not* examined by Goschy et al. (2014), who ignored the factor Target Position. We combined Goschy et al.’s (Exp. 1) data with newly acquired sets of data to raise our experimental power and support generalizability. The only difference in some of these new experiments was the nontarget color, which was blue instead of gray. Note that the nontarget color made no difference to the results, and even without the Goschy et al. data, the results would be essentially the same.

participants—while keeping the number of trials manageable and consistent with that in Experiment 1 of Goschy et al. (2014)—by combining the data from several experiments with, in all important respects, identical designs.

## Method

### Participants

One hundred and eighty-four (122 female, 62 male) right-handed observers, with a median age of 26 years (range: 18–65), participated in the main experiment of this study. They were recruited from the participant panels at Ludwig Maximilian University Munich and Birkbeck College, University of London. All of them reported normal or corrected-to-normal (color) vision and gave prior informed consent. They received €8 (or the GBP equivalent) per hour in compensation. Note that partial results based on the data of 25 of these participants were already reported in Goschy et al. (2014). One participant had to be removed from the analyses for missing data (see the [Appendix](#)).

### Apparatus

The experiment was conducted in a sound-reduced, moderately lit test chamber. The search displays were presented on a CRT monitor with a  $1,024 \times 768$  pixel screen resolution and a refresh rate of 120 Hz. The stimuli were generated using either the Experiment Toolbox (Reutter & Zehetleitner, 2012), with a Psychophysics Toolbox 3.0.9 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007) extension for MATLAB R2007a (The MathWorks Inc), or OpenSesame 3.0 (Mathôt, Schreijf, & Theeuwes, 2012) using a PsychoPy (Peirce, 2007) back end. The observers issued their responses using a QWERTZ [or QUERTY, at Birkbeck] keyboard by pressing the “y” [or the “z”] versus the “m” key with their left- versus their right-hand index finger, respectively.

### Stimuli

The stimulus displays were presented on a black background. They consisted of gray (RGB: 127, 127, 127; CIE [Yxy]: 21.22, 0.32, 0.32; for 112 participants) or light blue (RGB: 0, 140, 209; CIE [Yxy]: 57.3, 0.20, 0.20; for 72 participants) vertical nontarget bars ( $0.25^\circ$  of visual angle wide,  $1.35^\circ$  high), with their centers arranged equidistantly on three imaginary concentric circles with radii of  $2^\circ$ ,  $4^\circ$ , and  $6^\circ$ , comprising of 6, 12, and 18 bars, respectively. A further bar occupied the position in the center of the three circles. In every bar, there was a gap of  $0.25^\circ$  in height, which was randomly located  $0.25^\circ$  from the top or bottom of the bar. The target differed from the nontargets by its unique orientation, randomly

assigned on each trial: It was tilted  $12^\circ$  to either the right or the left. Note that  $12^\circ$ -tilted targets (among vertical nontargets) produce reliable “pop-out,” as evidenced by a flat search response times (RT)/set size function (with a slope near 0 ms/item) for such targets (Liesefeld, Moran, Usher, Müller, & Zehetleitner, 2016), indicative of “efficient” search.

If a singleton distractor was present, one of the nontargets was tilted  $90^\circ$  (horizontal; same-dimension distractor), instead of being vertical, or one of the nontargets was red (RGB: 255, 33, 51; CIE [Yxy]: 56.5, 0.60, 0.32), instead of gray (different-dimension distractor).

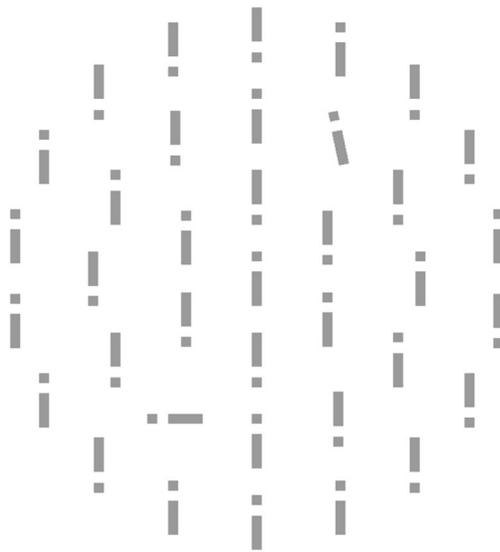
Note that the singleton target and (if presented) the singleton distractor could appear only at one of the 12 locations on the intermediate circle (i.e., singleton eccentricity was held constant). The nontarget stimuli on the outer and inner circles (together with those on the intermediate circle) essentially served to equate local feature contrast among the various singleton positions (e.g., Bravo & Nakayama, 1992; Nothdurft, 1993).

### Design

The type of the singleton distractor (same- or different-dimension) was introduced as a between-subjects factor, with 56 observers in the same-dimension condition and 128 in the different-dimension condition (including the 25 from Goschy et al., 2014, Exp. 1).

In addition to the type of distractor, the frequency distribution of the singleton distractor across the top and bottom halves of the search displays<sup>4</sup> was manipulated as a between-subjects factor, with the top half ranging from the 10 o'clock to the 2 o'clock positions and the bottom half from the 4 o'clock to the 8 o'clock positions on the intermediate circle (see Fig. 1). For half of the participants, the top semicircle was the frequent-distractor area (10 o'clock to 2 o'clock positions); for the other half, the bottom semicircle was the frequent-distractor area (4 o'clock to 8 o'clock positions). Neither the distractor nor the target could appear at the 3 and 9 o'clock positions, since these positions could not be unambiguously assigned to the frequent or the rare area. A distractor was present in a random 50% of the displays per block. If a distractor was present, it appeared in the frequent area about 90% of the time (“frequent distractors”) and in the rare area about 10% of the time (“rare distractors”). The target appeared equally often in both areas, with equal probabilities of appearing in all ten possible positions, but it never occurred at the same position as the distractor. The order of the trials

<sup>4</sup> In Experiment 1 of Goschy et al. (2014), in addition to the top–bottom manipulation of distractor frequency described here, there was also a left–right manipulation. Importantly, both “polarity” manipulations produced comparable patterns of distractor interference effects; that is, no main or interaction effects emerged involving the factor Polarity. Given this, only the top–bottom manipulation was used in further sampling for the present study.



**Fig. 1** Example of a stimulus display. The search target is the 12°-tilted bar at the 1 o'clock position, and the (same-dimension) distractor is the 90°-tilted bar at the 7 o'clock position.

within each block was randomized. The experiment consisted of 800 trials in total, subdivided into eight blocks of 100 trials each.

## Procedure

The experimental procedure was identical to that used by Goschy et al. (2014) in their Experiment 1. All observers were instructed both in writing and orally that their task was to discern whether the target bar was interrupted (by a gap) at the top or the bottom. If it was interrupted at the bottom, participants had to press the “y” [“z”] key; if it was interrupted at the top, they had to press the “m” key. They were informed that on some trials, there would be a horizontal (same-dimension condition) or, respectively, a red (different-dimension condition) distractor bar that they should simply ignore, since it would be irrelevant to their task. Note that the distractor-defining feature was deliberately fixed, to permit observers to operate a feature-based suppression strategy (see the “feature-weighting” account above). Observers were not informed that the distractor would be more likely to appear in one particular semicircle.

Each trial started with a white fixation cross in the middle of the screen, presented for a random duration between 700 and 1,100 ms. Then the search display appeared and stayed on until the observer had given a response indicating the gap position in the target bar. If the answer was incorrect, the word “Error” appeared in the center of the screen for 500 ms. Then the next trial started with the onset of the central fixation cross. After each block of trials, observers received RT and accuracy feedback and were free to take a short break before resuming the experiment.

After completing the experiment, participants filled in a brief questionnaire, which was intended to establish whether they had gained any explicit knowledge of the singleton distractors’ spatial frequency distribution (five response alternatives; i.e., were the distractors equally likely in all display parts, or were they more likely to appear in the upper, lower, left, or right display half?).

## Analysis

For the RT analyses presented below, we performed no (further) outlier rejection and computed median RT values per participant. We chose Cohen’s *d* to assess effect sizes. Apart from classical frequentist measures, to address issues raised by the ongoing “replication crisis” (cf. Open Science Collaboration, 2015), acknowledged by 90% of scientists (Baker, 2016), for our critical *t* tests we further report (1) the 95% highest-posterior-density intervals (HPD), computed with the “coda” package (Plummer, Best, Cowles, & Vines, 2006) for R (R Core Team, 2014), as the credibility interval, which is a Bayesian parameter estimate (similar to confidence intervals); and (2) standard JZS prior  $BF_{10}$  Bayes factors (Rouder, Speckman, Sun, Morey, & Iverson, 2009), computed with the BayesFactor package (Morey, Rouder, & Jamil, 2014) for R.  $BF_{10}$  gives the relative evidence of the data in favor of  $H_1$  as compared to  $H_0$ —that is, the likelihood with which  $H_1$  predicts the observed data better than  $H_0$  (see also Wagenmakers, 2007).

## Results

To examine for pure statistical learning effects (here: learning of the distractor frequency distribution), potentially confounding effects arising from (1) certain intertrial transitions, as well as (2) effects attributable to differential target-to-distractor distances between the critical conditions, must be eliminated from the data set. Such effects were indeed observed and were subsequently eliminated. These effects exhibited interesting differential patterns between the same- and different-dimension distractor conditions. Although the effects are tangential to our main findings, we feel that they are of significant methodological importance and theoretical interest. Therefore, we report all analyses in detail in the Supplementary Results section of the Appendix and discuss the major findings in the Discussion.

## Analysis of distractor interference effects

Our main prediction, derived from the dimension-weighting account, was that the mechanisms underlying the distractor probability-cueing effect (evidenced by reduced interference by distractors in the frequent vs. the rare area) would give rise

to impaired target processing only for targets defined within the same dimension as (but not for targets defined in a different dimension from) the distractor, and only for same-dimension targets located in the frequent (but not for targets in the rare) distractor region. To seek this effect pattern, we first conducted an overall analysis of variance (ANOVA) over the whole data set to establish any interaction patterns. On this basis, we looked for the existence of probability-cueing effects for both same- and different-dimension distractors, with a focus on differential target- (or position-)related effects between the frequent and rare-distractor areas. Finally, as a strong test of differential target-related effects, we directly looked for the predicted pattern on distractor-absent trials, specifically: Would target processing be (differentially) impaired in the frequent-distractor region even when there was no distractor in the display to actually cause interference?

Participants' median correct RTs<sup>5</sup> (for confound-free trials; see the Appendix) were first subjected to an overall (mixed-design) ANOVA with the main terms distractor type (same vs. different dimension), distractor location (distractor in frequent area, in rare area, absent), and target location (target in frequent- vs. rare-distractor area). This analysis revealed all main effects and two of the three two-way interactions—importantly, both involving the factor Distractor Type—to be significant<sup>6</sup> (for a visualization, see Fig. 2). To elucidate the origins of the significant two-way interactions, the same- and different-dimension distractor conditions were examined in two separate (repeated measures) ANOVAs with the factors Distractor Condition (distractor in frequent region, in rare region, absent) and Target Location (target in frequent- or rare-distractor region).

**Effects for same-dimension distractors** For same-dimension distractors, the ANOVA revealed both main effects to be significant: distractor location,  $F(2, 110) = 200.35, p < .001, \eta_p^2 = .78$ , and target location,  $F(1, 55) = 13.68, p < .001, \eta_p^2 = .20$ ; the interaction was not significant,  $F(2, 110) = 1.74, p = .181, \eta_p^2 = .03$ .

To ascertain that distractors generally caused interference, we directly compared RTs on distractor-present trials with those on distractor-absent trials: RTs were overall slower, by 94 ms, when a distractor was present than when it was absent

<sup>5</sup> Note that the error rates (overall error rate: 3.5%) were not influenced by distractor type (same vs. different dimension),  $F(1, 181) = 1.50, p = .222, \eta_p^2 = .01$ ; distractor location (frequent area, rare area, absent),  $F(2, 362) = 0.135, p = .874, \eta_p^2 = .00$ ; or target location (frequent area, rare area),  $F(1, 181) = 0.175, p = .677, \eta_p^2 = .00$ . Also, none of the interactions was significant.

<sup>6</sup> Main effects: distractor type,  $F(1, 181) = 30.34, p < .001, \eta_p^2 = .14$ ; distractor location,  $F(2, 362) = 220.16, p < .001, \eta_p^2 = .55$ ; and target location,  $F(1, 181) = 9.62, p = .002, \eta_p^2 = .05$ . Interactions: Distractor Type  $\times$  Distractor Location,  $F(2, 362) = 91.71, p < .001, \eta_p^2 = .34$ ; and Distractor Type  $\times$  Target Location,  $F(1, 181) = 9.38, p = .003, \eta_p^2 = .05$ . The Distractor Condition  $\times$  Target Location,  $F(2, 362) = 0.75, p = .471, \eta_p^2 = .00$ , and Distractor Type  $\times$  Distractor Location  $\times$  Target Location,  $F(2, 362) = 1.53, p = .219, \eta_p^2 = .01$ , interactions were not significant.

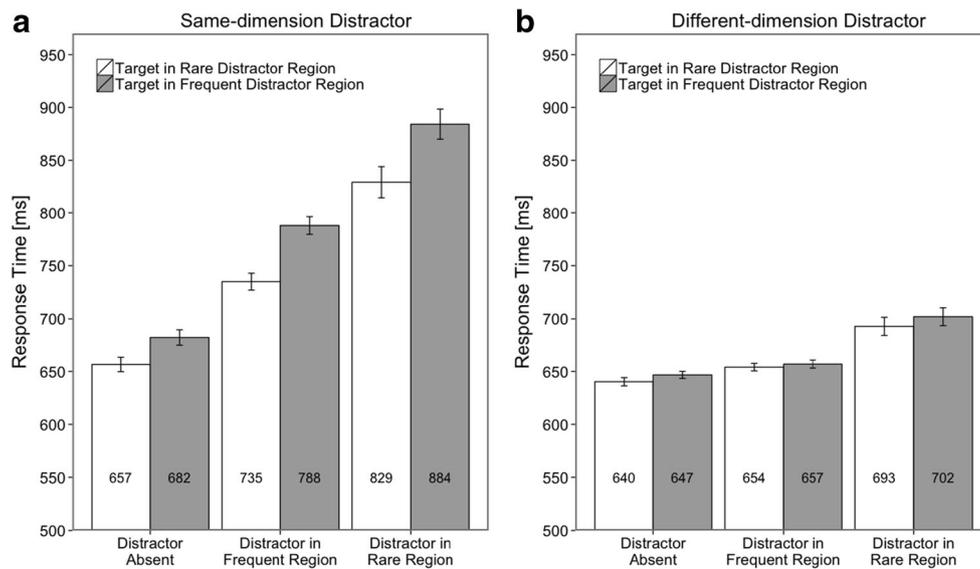
(761 vs. 667 ms),  $t(55) = 14.94, p < .001, d_z = 2.00$ , 95% HPD [81 ms, 106 ms],  $BF_{10} = 8.80 \times 10^{17}$ . To directly test for a probability-cueing effect, we contrasted the frequent- versus rare-distractor-present conditions: RTs were indeed faster, by 97 ms, when a distractor was presented in the frequent rather than the rare area (751 vs. 848 ms),  $t(55) = -9.40, p < .001, d_z = 1.26$ , 95% HPD [-116 ms, -73 ms],  $BF_{10} = 3.27 \times 10^{10}$ . Finally, we examined the net distractor interference effect with reference to distractor-absent trials for the frequent and rare areas separately. Both effects were significant (distractors in rare area: 181 ms;  $t(55) = 15.02, p < .001, d_z = 2.01$ , 95% HPD [158 ms, 205 ms],  $BF_{10} = 1.12 \times 10^{18}$ ; distractors in frequent area: 84 ms;  $t(55) = 13.75, p < .001, d_z = 1.84$ , 95% HPD [72 ms, 96 ms],  $BF_{10} = 2.59 \times 10^{16}$ ), with distractors in the rare area causing greater interference than distractors in the frequent area.

Although the Distractor Condition  $\times$  Target Location interaction was not significant—indicative of an additive target location effect for all three distractor conditions—the target location effect was numerically smaller when a distractor was absent in the display (25 ms) than when one was present in the frequent- or the rare-distractor region (53 or 55 ms, respectively). Despite being reduced, the effect on distractor-absent trials was still significant: RTs were slower to targets appearing in the frequent versus the rare region (682 vs. 657 ms),  $t(55) = 3.70, p < .001, d_z = .49$ , 95% HPD [38 ms, 12 ms],  $BF_{10} = 51$ .

Thus, as expected (according to the DWA), we found a significant effect of target location, with slower RTs when the target appeared in the frequent- as compared to the rare-distractor area. Importantly, this effect was evident even when distractors were absent—that is, when there could not be any distractor interference. This pattern provides strong support for the frequent-distractor area being suppressed as a result of distractor (distribution) probability learning affecting processing of the target as well as that of the distractor.

**Effects for different-dimension distractors** For different-dimension distractors, the ANOVA also revealed a significant main effect of distractor condition [ $F(2, 252) = 61.64, p < .001, \eta_p^2 = .33$ ], but (in contrast to same-dimension distractors) not for target location [ $F(1, 126) = 0.92, p = .339, \eta_p^2 = .01$ ]; the interaction was also not significant [ $F(2, 252) = 0.19, p < .827, \eta_p^2 = .00$ ].

Distractors again caused general interference (main effect of distractor condition): RTs were slightly, but significantly, slower overall on distractor-present than on distractor-absent trials (656 vs. 642 ms),  $t(126) = 6.73, p < .001, d_z = 0.60$ , 95% HPD [10 ms, 18 ms],  $BF_{10} = 1.76 \times 10^7$ ; note that this interference effect was much smaller than that with same-dimension distractors (14 vs. 94 ms). Furthermore, a comparison of the frequent- versus the rare-distractor-present condition revealed RTs to indeed be faster when a distractor was



**Fig. 2** Mean response times (RTs, calculated across participants' median RTs) for targets appearing in the frequent- versus the rare-distractor region, as a function of the distractor condition (absent distractor, distractor in the frequent-distractor region, distractor in the rare-distractor region) in (A) the same-dimension distractor condition (horizontal, orientation-

defined distractor) and (B) the different-dimension distractor condition (red, color-defined distractor). In both conditions, the distractor bar was presented among gray vertical bars and a slightly tilted gray target bar. Error bars depict the within-subjects SEMs (Morey, 2008).

presented in the frequent rather than in the rare area (654 vs. 689 ms),  $t(126) = -6.10$ ,  $p < .001$ ,  $d_z = 0.54$ , 95% HPD [-46 ms, -23 ms],  $BF_{10} = 1.73 \times 10^6$ , though this probability-cueing effect, too, was much smaller than that with same-dimension distractors (35 vs. 87 ms). Finally, as expected, the net distractor interference effect with reference to distractor-absent trials was greater for distractors in the rare area (47 ms),  $t(126) = 7.74$ ,  $p < .001$ ,  $d_z = 0.69$ , 95% HPD [34 ms, 59 ms],  $BF_{10} = 2.79 \times 10^9$ , than for distractors in the frequent area (11 ms),  $t(127) = 5.93$ ,  $p < .001$ ,  $d_z = 0.53$ , 95% HPD [7 ms, 15 ms],  $BF_{10} = 4.05 \times 10^5$ ; these net effects of 47 ms (rare area) and 11 ms (frequent area) compared with effects of 181 ms and, respectively, 84 ms for same-dimension distractors.

Concerning the (nonsignificant) target location effect, RTs were overall only slightly slower to targets in the frequent-distractor than to targets in the rare-distractor area. This effect was nonsignificant for all three distractor conditions (distractor absent: 647 vs. 640 ms,  $t(126) = 1.43$ ,  $p = .154$ ,  $d_z = 0.13$ , 95% HPD [15 ms, -2 ms],  $BF_{10} = 0.27$ ; distractor in frequent area: 657 vs. 654 ms,  $t(126) = 0.56$ ,  $p = .580$ ,  $d_z = 0.04$ , 95% HPD [12 ms, -8 ms],  $BF_{10} = 0.11$ ; distractor in rare area: 702 vs. 693 ms,  $t(126) = -0.69$ ,  $p = .493$ ,  $d_z = 0.06$ , 95% HPD [34 ms, -17 ms],  $BF_{10} = 0.12$ ).

**Distractor-absent trials** Arguably, the strongest evidence for learned, persistent spatial suppression on the master saliency map, or the lack of it, would be derived from distractor-absent trials, in which spatial suppression of target processing can be assessed in its pure form, without any effect of a competing distractor. Thus, to examine for differential suppression

patterns between same- and different-dimension distractors, we directly compared and contrasted the effects of the two distractor types in the distractor-absent condition, in a Distractor Type  $\times$  Target Location (mixed-design) ANOVA. This analysis revealed a significant main effect of target position [ $F(1, 181) = 10.71$ ,  $p = .001$ ,  $\eta_p^2 = .06$ ], whereas the main effect of distractor type was nonsignificant [ $F(1, 181) = 3.11$ ,  $p = .079$ ,  $\eta_p^2 = .01$ ]. Importantly, the effect of target location was significantly modulated by the distractor type [ $F(1, 181) = 5.58$ ,  $p = .019$ ,  $\eta_p^2 = .03$ ]. Given this interaction, we compared the target location effects (i.e., the mean differences between the two target location conditions) between same- and different-dimension distractors. The results were in line with our hypothesis: The target location effect (the disadvantage for targets appearing in the frequent vs. the rare area) was significantly larger with same-dimension (26 ms) than with different-dimension (6 ms) distractors:  $t(181) = 2.36$ ,  $p = .019$ ,  $d = 0.38$ , 95% HPD [8 ms, 24 ms],  $BF_{10} = 4.4$ . Additionally, the target location effect differed significantly from 0 for same-dimension distractors,  $t(55) = 3.70$ ,  $p < .001$ ,  $d_z = .49$ , 95% HPD [11 ms, 39 ms],  $BF_{10} = 51$ , but not for different-dimension distractors,  $t(126) = 1.43$ ,  $p = .154$ ,  $d_z = 0.13$ , 95% HPD [-2 ms, 15 ms],  $BF_{10} = 0.27$ ).

## Postexperiment questionnaires

We also examined whether the interference reduction for the frequent- versus the rare-distractor area depended on participants having “recognized” the frequency distribution. If so, this would imply that the suppression of distractors in the

frequent area might have relied on a conscious effort. In the postexperimental questionnaire, 43 of the 183 (23%) participants indicated the distractor frequency distribution correctly. Although this might be seen as chance level (recall that there were five response alternatives, so chance level would be 20%), it should be noted that the majority of participants (53%) opted for the response “equal distribution,” rather than committing to a specific region in which distractors were (believed to be) likely.<sup>7</sup> When committing to a specific response, the correct distractor region was significantly more likely to be chosen than any of the three alternatives (55% vs. 45% [= 3 × 15%];  $\chi^2(1) = 30.73$ ,  $p < .001$ )—indicative of a degree of awareness of the actual distractor distribution. Importantly, the degree of “awareness” was little influenced by the distractor type: 20% and 25% correct answers (given five response alternatives, including the “equal-distribution” option) with same- and different-dimension distractors, respectively. Of those who committed to a specific response, 48% [same-dimension distractors,  $\chi^2(1) = 4.15$ ,  $p = .042$ ] and 57% [different-dimension distractors,  $\chi^2(1) = 23.76$ ,  $p < .001$ ] answered correctly.

Comparing participants who answered correctly with those who responded incorrectly (including those who gave an “equal-distribution” answer) in an Awareness (correct vs. incorrect answer) × Distractor Type (same- vs. different-dimension) × Distractor Location (frequent vs. rare area) ANOVA of the median RTs revealed no two-way interactions involving awareness [Awareness × Distractor Type,  $F(1, 179) = 1.75$ ,  $p = .188$ ,  $\eta_p^2 = .01$ ; Awareness × Distractor Location,  $F(1, 179) = 3.21$ ,  $p = .075$ ,  $\eta_p^2 = .02$ ], but the three-way interaction was significant,  $F(1, 179) = 7.56$ ,  $p = .007$ ,  $\eta_p^2 = .04$ . Follow-up ANOVAs with the factors Awareness and Distractor Location, calculated separately for each distractor-type condition, failed to reveal significant main effects of awareness for both different-dimension and same-dimension distractors [different-dimension distractors,  $F(1, 125) = 0.03$ ,  $p = .858$ ,  $\eta_p^2 = .00$ ; same-dimension distractors,  $F(1, 54) = 2.65$ ,  $p = .110$ ,  $\eta_p^2 = .05$ ]. However, for the same-dimension distractors [but not for the different-dimension distractors,  $F(1, 125) = 0.01$ ,  $p = .915$ ,  $\eta_p^2 = .00$ ], the Awareness × Distractor Location interaction was significant,  $F(1, 54) = 9.49$ ,  $p = .003$ ,  $\eta_p^2 = .15$ , reflecting the fact that (the 11) “aware” participants showed a larger probability-cueing effect than did (the 45) “nonaware” participants (158 vs. 83 ms),  $t(54) = 3.08$ ,  $p = .003$ ,  $d_z = 1.04$ , 95% HPD [91 ms, 141 ms],  $BF_{10} = 12$ . Given that the overall RTs were comparable between the “aware” and “nonaware” groups (774 vs. 745 ms),  $t(54) = 0.77$ ,  $p = .443$ ,  $d_z = 0.26$ , 95% HPD [720 ms, 793 ms],  $BF_{10} = 0.408$ , the larger probability-cueing effect for the “aware” participants provides an indication that, with same-dimension (but

not with different-dimension) distractors, the probability-cueing effect might have been (strategically) enhanced as a result of observers explicitly recognizing the display half in which the distractor was more or, respectively, less likely to appear.

## Discussion

The present study revealed a paramount difference in the probability-cueing effect between same- (orientation) and different- (color) dimension distractors in visual singleton search. Although both distractor-type groups showed significant learning of the spatial distractor distribution (as evidenced by reduced interference from distractors that appeared in the frequent, as compared to the rare, distractor area), the interference was higher overall—by a factor of at least 4—with same- relative to different-dimension distractors. In addition, there was a qualitative difference in the interference patterns caused by same- versus different-dimension distractors. Search under conditions of same-dimension distractors was associated with a target location effect (i.e., slowed responding to targets appearing in the frequent- vs. the rare-distractor region). This was observed even for displays that did not contain a distractor. No target location effect was evident in search under conditions of different-dimension distractors. We will discuss the implications of these effects in turn, while also touching upon the issue of the nature—implicit versus explicit—of distractor probability learning.

### Same-dimension distractors cause greater interference than different-dimension distractors

The differential magnitude of interference between same- and different-dimension distractors is in line with previous reports that distractors that are similar to the search target cause more interference to begin with (e.g., *DWA*: Müller et al., 2009; Zehetleitner et al., 2012; *ambiguity account*: Meeter & Olivers, 2006; Olivers & Meeter, 2006; Pashler, 1987).<sup>8</sup> Additionally, the present data show that shielding from the interference generated by distractors that occur frequently in a particular display area *cannot* be learned as effectively with target-similar as with target-dissimilar distractors: Same-dimension distractors continued to produce strong interference even in the frequent-distractor area, which compares with weak interference by frequent-area distractors in the different-dimension condition.

<sup>8</sup> Although this pattern can be described in terms of *similarity* (or *ambiguity*), we propose that it reflects fundamental, dimension-based constraints in the functional architecture of search guidance. Further research will be necessary to discriminate between the essentially continuous similarity (or ambiguity) versus discrete dimension-based accounts.

<sup>7</sup> Note that the response alternative “equal distribution” was introduced in order to exactly follow the awareness test procedure of Goschy et al. (2014).

This effect pattern argues against feature-based accounts, according to which distractor suppression is achieved by the independent down-weighting of distractor features (first-order feature suppression) and/or up-weighting of target features. In theory (cf. Wolfe, Friedman-Hill, Stewart, & O’Connell, 1992; Wolfe & Horowitz, 2017), independent weighting of (target) features should work effectively as long as the features are clearly separable. In the present study, this was the case not only in the different-dimension condition, but also in the same-dimension condition: The distractor was consistently rotated by 90° from the vertical, as compared to a variable (left or right) target tilt of 12°. According to Wolfe et al. (1992), this is a “categorical” feature difference, capable of guiding search. Apparently, however, this categorical difference could not be exploited by the participants in the same-dimension distractor condition, effectively ruling out a strict, feature-based account (at least for the orientation dimension).

Instead, a straightforward, mechanistic account of the differential interference between same- and different-dimension distractors effects is provided by the DWA: Due to the (assumed) hierarchical organization of saliency computation and dimensionally coupled weighting of feature contrast signals (e.g., Zehetleitner et al., 2012), it is harder to suppress known distractors defined by features in the same dimension as the target, than to suppress features in a different dimension. As will be detailed below, DWA readily explains why distractor interference is greatly increased overall in the same-dimension, as compared to the different-dimension, condition (94 vs. 14 ms). Interference effects approaching 100 ms suggest that attention was actually captured by the distractor on a large majority of trials (consistent with Liesefeld et al., 2017, who also used orientation-defined distractors and targets).

### Differential mechanisms underlie the probability-cueing effects in same- versus different-dimension distractors

The differential pattern of distractor location probability-cueing effects—specifically, the differential target location effects between the same- and different-dimension conditions—cannot be explained by spatially selective versions of either feature-based (or first-order feature) suppression models or master-map-based suppression models. Master-map-based suppression would predict *impaired* processing of targets in the frequent-distractor region, regardless of whether the distractor is defined in the same or a different dimension to the target. Feature-based suppression models would always predict *unimpaired* processing of targets in the frequent-distractor region, regardless of whether distractors are defined in the same or a different dimension

to the target. The fact that target processing in the frequent region was slowed only in the same-dimension, but not in the different-dimension, distractor condition effectively rules out that either of these mechanisms can account for the present set of findings on its own.

But this pattern is consistent with the DWA, according to which the distractor-defining dimension can be suppressed as a whole, with greater suppression applied to the frequent- than to the rare-distractor area. However, dimension-based (or second-order feature) suppression would leave target processing unaffected only when the distractor is defined in a different dimension to the target. By contrast, when the distractor is defined in the same dimension as the target, two strategies of reducing distractor interference would be available: dimension-based suppression or master-map-based suppression, in both cases with stronger suppression assigned to the frequent- than to the rare-distractor region, but which in both cases would also impair target processing. With both strategies, the power of distractors appearing in the frequent area to capture attention would be reduced, as compared to distractors in the rare area, giving rise to probability-cueing effects. But the downside would be that targets within the frequent (i.e., suppressed) region would be responded to *slower* than targets in the rare region. Both of these effects were evidenced by the data, consistent with either of the two strategies.

With same-dimension distractors, dimension-based suppression would appear to be a less plausible strategy than master-map-based suppression, as any down-weighting of the orientation dimension would conflict with the task of finding the orientation-defined target.<sup>9</sup> However, no such conflict would arise if the down-modulation is applied to the (spatial) master saliency map. This representation is assumed to be feature- and dimension-less. Master map activations as such convey no information as to how, by which feature and in which dimension, they were produced. Rather, post-selective back-tracking to lower, dimension- and feature-coding, levels may be required to extract this information (e.g., Töllner, Rangelov, & Müller, 2012). Given this, applying spatial inhibition at this level would conflict less with the goal of finding and responding to an orientation-defined target. Additionally, the target location effect was even evident on distractor-absent trials, strongly supporting spatially selective master-map-based suppression.

<sup>9</sup> To solve the task, observers would have to actively maintain a template of the orientation target in visual working memory, to decide whether a stimulus that summons attention is a target (rather than a distractor), as well as to top-down bias search toward stimuli matching the target description (e.g., Olivers, Peters, Houtkamp, & Roelfsema, 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). There would thus be a goal conflict within observers, who at the same time would be attempting to keep any signals from the orientation dimension out of the search and selectively enhancing the target orientation.

With different-dimension distractors, distractor interference can be rather effectively reduced by dimension-based suppression—as a result of which feature contrast signals from this dimension arrive attenuated at the saliency summation stage (the master map), reducing their power to capture attention. Importantly, to explain the probability-cueing effect (35 ms faster RTs to targets in the frequent vs. the rare area), one would have to additionally assume that, as a result of probability learning, the dimension-based down-modulation of feature contrast signals from the distractor dimension becomes stronger for the frequent- than for the rare-distractor area. Stronger down-modulation of feature contrast signals from the distractor dimension within the frequent area would leave target signals from another dimension unaffected. Consistent with this, RTs were *not* significantly slower to targets in the frequent area than to targets in the rare area.

Of note, this qualitative difference between the two distractor-type conditions is seen even in a comparison of the *distractor-absent* trials, in which no “confounding” by a competing additional singleton in the display was possible. Here, there was no reliable target location effect with different-dimension distractors, but a significant (26-ms) effect with same-dimension distractors—despite generally similar RT levels on distractor-absent trials (where the displays were identical for the two groups).

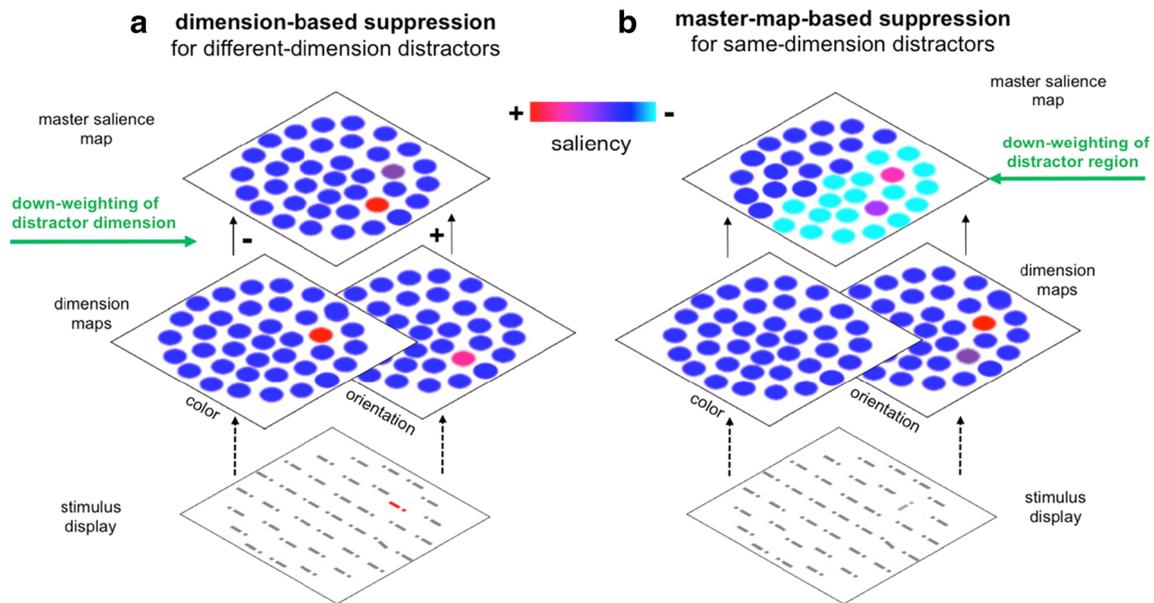
### Implications for the cognitive architecture underlying distractor probability cueing

These results have implications for drawing conclusions about the cognitive architecture mediating distractor probability (distribution) learning effects (see Fig. 3): Suppression of *different-dimension* distractors operates at a level below the master saliency map (Fig. 3A). Interfering feature contrast signals from the distractor-defining dimension are down-modulated so that their contribution to the overall saliency signaling is effectively reduced, yielding lower distractor interference overall; at the same time, feature contrast signals from the target dimension are left unaffected. By contrast, *same-dimension* distractors generate a comparatively large interference effect, and RTs are significantly slowed when the target appears in the frequent- as compared to the rare-distractor area—even when no distractor (which could cause interference) is actually present in the display. The latter effect is readily explained by assuming that the frequent-distractor region is suppressed either at the superordinate level of the master saliency map (Fig. 3B; our preferred account), or, alternatively, at the level of the orientation dimension map, which in both cases would affect the target as well as the distractor signals.

However, although the present findings are in line with the DWA (the only general account predicting a dissociation between same- and different-dimension distractors), further

work—for instance, with luminance-, color-, and motion-defined targets (and distractors defined in either the same dimension or one of the other dimensions)—will be necessary for the DWA to be established as a truly general account of the asymmetry revealed in the present study. Of note, there is evidence that, within the color dimension, salient singletons mismatching the target color (i.e., same-dimension distractors) may fail to capture attention. This has been demonstrated in contingent-capture studies, with temporally separated presentation of the singleton distractor and target displays (Folk, Leber, & Egeth, 2002; Lien, Ruthruff, & Cornett, 2010b; Lien, Ruthruff, & Johnston, 2010a), and in additional-singleton studies, with target and distractor in the same display (e.g., Gaspar, Christie, Prime, Joliceur, & McDonald, 2016; Gaspar & McDonald, 2014). In additional-singleton studies, nonmatching colors have usually interfered relatively little,<sup>10</sup> though there are exceptions; for instance, Kandel, Feldmann-Wüstefeld, and Schubö (2017) observed that, once participants had learned that green and blue singletons were response-relevant in a categorization task (green vs. blue response), they showed substantial interference, of 37 ms, by a red (i.e., non-target-colored) additional-singleton distractor in a compound-search task, along with ERP indices of attentional capture (see also Feldmann-Wüstefeld, Uengoer, & Schubö, 2015). Similarly, in the contingent-capture literature, although mismatching colors have usually produced relatively little interference, a more recent study revealed that with a target that could be either red or green, distractors in a nontarget color (blue) led to a capture effect comparably sized to those of target-colored distractors (whereas motion-defined distractors failed to capture attention; Harris, Becker, & Remington, 2015). Despite these exceptions (which are consistent with dimension-based attentional settings), in light of the balance of evidence, it would appear that the suppression of color distractors does involve an element of feature-based suppression (see also Gaspelin et al., 2015, and Gaspelin & Luck, *in press*, for evidence of first-order, as opposed to second-order, color feature suppression in a paradigm with shape targets and color distractors, where the distractor color was either constant/predictable (Gaspelin et al., 2015) or variable/nonpredictable (Gaspelin & Luck, *in press*) across trials). This picture is actually consistent with previous studies of dimension weighting

<sup>10</sup> For instance, in Gaspar and McDonald (2014, Exp. 1: yellow target, red distractor, presented among green nontargets), the color distractor generated significant interference of 18 ms; although it produced no N2pc (which would have been indicative of attentional capture), it did elicit a  $P_D$  (i.e., with a midline target, the event-related potential waveform was more positive contralateral vs. ipsilateral to the distractor 250–300 ms post display onset), which is thought to reflect—in this case feature-based—distractor suppression (e.g., Hickey, Di Lollo, & McDonald, 2009; Sawaki, Geng, & Luck, 2012). Note, though, that a significant  $P_D$  was evident only on fast-response trials, not on slow-response trials, suggesting failure of distractor suppression on some proportion of the (slow-response) trials.



**Fig. 3** Schematic representations of the two suppression models involved in the probability cueing of distractor locations that are supported by the data: (A) dimension-based suppression for different-dimension distractors and (B) master-map-based suppression for same-dimension distractors. The search display depicted at the bottom of each panel contains an orientation-defined target ( $12^\circ$ -tilted relative to the vertical non-targets) and (A) a color-defined (red bar) and (B) an orientation-defined (horizontal bar) distractor. The map in the middle of each figure represents the dimension map at which feature contrast signals are combined for separable feature dimensions (in the example, color and orientation). The map depicted at the top of each figure is the search-guiding “master saliency map.” In all maps, hotter colors depict higher and cooler colors lower saliencies. (A) In dimension-based suppression, the weighting of the target and distractor signals occurs at the level of the dimension maps—that is, feature weighting is dimensionally coupled, so that

distractor signals can be down-weighted without affecting target signals only when the target and distractor are defined in different dimensions. Note that, in panel A, the combined feature contrast signals from the color dimension are negatively weighted on their transfer to the master saliency map, reducing their impact on the overall saliency coding. Distractor probability cueing could be explained by greater down-weighting of signals from the distractor-defining dimension for the frequent (lower display half) than for the rare (upper half) distractor region; note that this differential down-weighting is not depicted in the figure. (B) For same-dimension distractors, distractor probability cueing could operate by spatially selective suppression of a whole region of the search display (in the example, the lower half) operating at the level of the master saliency map. With both mechanisms depicted, interference would be reduced for distractors appearing in the frequent- as compared to the rare-distractor region. See the text for further explanations.

(with combinations of color, motion, and orientation targets), in which color proved to be special: It was the only dimension producing significant feature-specific intertrial priming and trial-wise precueing effects<sup>11</sup> (e.g., Found & Müller, 1996; Müller et al., 2003; Weidner, Pollmann, Müller, & von Cramon, 2002)—underscoring the dictum that “not all

<sup>11</sup> For instance, Found and Müller (1996) found that, in color–orientation pop-out search, repetition of the precise target color feature across trials (e.g., red → red) conferred an advantage over a color switch (e.g., blue → red), with the latter yielding an advantage as compared to a dimension switch (e.g., right-tilted → red). With orientation-defined targets, by contrast, only a dimension-specific switch effect was seen. Similarly, Müller et al. (2003) found that when a particular target color was precued to be likely at the start of a trial (e.g., red, cue validity  $p = .79$ ), there was a significant advantage for targets singled out by this feature as compared to targets defined by another color feature (e.g., blue,  $p = .07$ ) or by an orientation feature ( $45^\circ$  left or right tilt, each  $p = .07$ ). Of note, there was also some advantage for targets defined by the non-cued color feature (i.e., blue when the cue indicated red; same-dimension feature) as compared to the two orientation features (different-dimension features), even though all non-cued features were equally unlikely. For orientation-defined targets, by contrast, there was no significant feature-specific cueing effect—that is, no graded advantage for the cued versus the non-cued orientation feature. These results point to a greater role of feature-specific coding for the color relative to the orientation dimension.

features or dimensions were created alike” (e.g., Nothdurft, 1993; Wolfe, Chun, & Friedman-Hill, 1995). Accordingly, feature-based distractor suppression may be possible, to some extent, with color distractors (which produce relatively small intra-dimensional interference effects; e.g., Gaspar et al., 2016; Gaspar & McDonald, 2014), whereas it does not appear to be possible with orientation distractors (which produce large intra-dimensional interference effects; e.g., Liesefeld et al., 2017, and the present study). Nevertheless, given the available evidence from dimension-weighting studies, we would predict dimension-based effects to outweigh feature-based effects even with color distractors. Purpose-designed studies, with carefully calibrated color and orientation stimuli, as well as generalization to other combinations of singleton (target and distractor) dimensions involving luminance, color, and motion stimuli, would be necessary to examine this prediction. This is beyond the scope of the present study.

Assuming reasonable generalizability, note that the search architecture envisaged by DWA does not exclude feature-based selection—which is, after all, assumed to be the prime principle of non-spatial selection in virtually all models of

visual search and selective attention (*Guided Search*: e.g., Wolfe, 2007; *template-based guidance*: e.g., Duncan & Humphreys, 1992). DWA only claims that for features defined within the same dimension, one cannot independently modulate one feature contrast signal (e.g., the target signal) from another (e.g., the distractor signal) as regards their cross-dimensional *integration/summation weights* by units of the master saliency map. Although some theorists have criticized DWA for being unable to account for findings of feature selectivity, one straightforward extension would be to assume a combination of independent intra- and cross-dimensional weights: intra-dimensional weights would ensure that one can, to some extent, up-modulate the target feature and/or down-modulate the distractor feature in the computation of dimension-specific (i.e., within-dimensions) feature contrast signals (as assumed by, e.g., Guided Search). However, both these (feature-weighted) signals would then be multiplied by the same dimensional weight on being transferred to the master saliency map. Such a scheme would ensure an element of feature selectivity, while also maintaining the principle of dimensional weight coupling—which is at the heart of DWA.

### Distractor probability cueing: explicit or implicit in nature?

In previous studies of distractor location probability cueing (Goschy et al., 2014; Leber et al., 2016), participants were typically unable, at the end of a lengthy experiment, to tell at above-chance level at which locations distractors were likely to appear. This was taken to suggest that the distractor probability cueing effect is essentially implicit in nature (Reder et al., 2003, too, assume that their *negative location priming* effect operates outside conscious awareness, though without having examined for this). However, all these studies employed only relatively small numbers observers (e.g., 19 participants in Goschy et al., 2014; 26 participants in Leber et al., 2016), making it hard to actually establish above-chance recognition of the likely distractor locations. Given our large sample, we had reasonable power to determine whether participants could tell above chance in which display region a distractor was most likely to appear. Although responses appeared to be at chance when looking at the proportion of participants who correctly selected the frequent-distractor region (out of the total number of observers), a more detailed analysis revealed significant above-chance performance among those participants who did not choose a noncommittal, “equal-distribution” response. This was the case whether participants had performed the task under the different- or the same-dimension distractor condition. Because same-dimension distractors caused massive interference, one could have surmised that a majority of observers might have become aware of the unequal distribution—which was, however, not borne out by the data.

Partitioning the participants into two “awareness” groups (“aware” = correct answer, “unaware” = incorrect answer) and reexamining the probability-cueing effect as a function of group revealed no significant main effect of “awareness.” However, there was an interaction of “awareness” with distractor condition for the same-dimension group, with “aware” participants exhibiting a larger probability-cueing effect (157 ms, which compares with 83 ms—i.e., half the effect—for the “nonaware” group), without responding significantly slower. This would argue that (perhaps the majority of) these 11 observers became genuinely aware of the distractor frequency distribution, which made them increase the inhibition they applied to the frequent-distractor area. Of note this would predict that aware participants also exhibit an enlarged target position effect—which is, at least numerically, borne out by the data. Note, however, that above chance performance does not necessarily imply awareness, and further studies are necessary to resolve this question (ideally excluding the “equal-distribution” response and including confidence ratings).

Thus, our data provide some indication (at variance with Goschy et al., 2014, who had only a small sample of participants, as compared to the one analyzed in the present study, and who examined only correct versus all incorrect, including “equal-distribution,” responses) that distractor probability cueing might reflect, at least to some extent, an explicit learning effect. This would place distractor probability cueing with other, perceptual-learning effects in the search literature, notably *contextual cueing*—an effect that is similarly associated with a (limited) degree of explicit awareness of repeatedly encountered target–nontarget configurations (Smyth & Shanks, 2008, and Vadillo, Konstantinidis & Shanks, 2015; though see Chun & Jiang, 2003; Colagiuri & Livesey, 2016; Goujon, Didierjean, & Thorpe, 2015). Note, though, that whether conscious awareness drives distractor probability cueing is another matter: Conceivably, the effect may be implicitly driven, while being associated with (a degree of) explicit awareness (see Geyer, Müller, Assumpção, & Gais, 2013, with regard to contextual cueing). However, with same-dimension distractors—which require enhanced cognitive control to deal with capture events—observers who became consciously aware of the distractor distribution appeared to adjust the strength of spatial suppression accordingly. No such adaptation was evident with different-dimension distractors, presumably because these require a lesser degree of cognitive control to be filtered out effectively.

### Location-specific inter-trial and lateral-inhibition effects

The supplementary analyses (see the Appendix for details) revealed significant modulations of RTs by positional intertrial effects, in particular, expedited RTs when the current (trial  $n$ )

target appeared at the location of the previous (trial  $n - 1$ ) target ( $T_{n-1}-T_n$  transition)—in line with the *positional*-priming literature in visual search (e.g., Geyer, Müller, & Krummenacher, 2007; Kumada & Humphreys, 2002; Maljkovic & Nakayama, 1996). This is interesting because we used relatively dense displays (with 36 items), whereas hitherto positional intertrial effects have been investigated and reported mainly with relatively sparse displays (as with the *priming of pop-out* paradigm, in which displays typically consist only of three relatively widely spaced items). On the other hand, positional inter-trial priming effects have been reported by Krummenacher et al. (2009) for both singleton detection and compound-search tasks (both with dense displays): RTs were expedited to targets on trial  $n$  that appeared at (roughly) the same position as the target on trial  $n - 1$ , and this effect was more marked for compound-search than for simple detection tasks, even though the target singleton was exactly the same in both cases. Related to distractor probability cueing, Goschy et al. (2014) had found evidence that, to some extent, the interference reduction for the frequent (as compared to the rare) distractor area was due to positional inter-trial effects, in particular: Interference was reduced when the distractor on the current trial occurred at the same location as the previous distractor ( $D_{n-1}-T_n$  transition)—a finding confirmed in the present study. Additionally, the present, more comprehensive inter-trial analysis showed that if a target appears at the same location as the last distractor ( $D_{n-1}-T_n$  transition) or if a distractor occurs at the same location as the last target ( $T_{n-1}-D_n$  transition), RTs are slowed. Given that such repetition effects were much more likely to happen in the frequent- than in the rare-distractor area, they would have affected both areas differentially and thereby confounded the results. This highlights the necessity to control for positional inter-trial effects when examining effects of distractor location probability cueing.

Theoretically of potential importance, the inter-trial transition effects—that is, both the (inter-trial) distractor location inhibition ( $D_{n-1}-T_n$  trials: 53 vs. 13 ms;  $D_{n-1}-D_n$  trials:  $-32$  vs.  $-2$  ms), and to some extent also the target location facilitation (at least on  $T_{n-1}-T_n$  trials:  $-70$  vs.  $-49$  ms)—were greatly increased in the same-dimension, relative to the different-dimension, condition (with distractor location inhibition being increased by a factor of at least 4!).

In addition to positional intertrial effects, the supplementary analyses revealed significant intra-trial modulations of RTs by the spatial distance of the target relative to the distractor. It is thought that when a salient distractor captures attention, it must be (actively) suppressed for focal attention to move on to the next most salient item, the target (see, e.g., Liesefeld et al., 2017), and this suppression affects not only the distractor location itself, but

spreads laterally to the surrounding region, tailing off gradually with increasing distance from the distractor location (e.g., Gaspar & McDonald, 2014; Mathôt, Hickey, & Theeuwes, 2010; Mounts, 2000).<sup>12</sup>

Importantly, in the present study, this intratrial lateral inhibition effect centered on the distractor position was also greatly increased, by a factor of 3, for the same-dimension relative to the different-dimension distractors (measured in terms of the rate of RT decrease as a function of the distance of the target from the distractor:  $-12.99$  vs.  $-4.72$  ms per degree of visual angle). This pattern mirrors the increased cross-trial distractor location inhibition with same-dimension as compared to different-dimension distractors, suggesting that it is the inhibition brought to bear on the distractor on a given (distractor-present) trial that is then carried over into the next trial.

Overall, this pattern is consistent with the idea that the harder the search and, particularly, the harder it is to shield from distractor interference, the greater the positional intra- and intertrial effect. Concerning the intratrial inhibition (and the cross-trial carryover of inhibition) of the distractor location, the more likely it is that the distractor captures attention, the greater the suppression applied. There may be two explanations for this: One is that, on a given trial, the amount of inhibition placed on the distractor location is increased in the different-dimension, as compared to the same-dimension, distractor condition. Alternatively, the amount of inhibition is the same on a single-trial basis, but given that same-dimension distractors generate capture more frequently (i.e., on a greater number of trials), these also have to be actively suppressed more frequently (on a greater number of trials), giving rise to an, on average (i.e., across trials), increased inhibition effect in this condition. The idea is that a distractor that captured attention (once it is established by a post-selective analysis process that it is a distractor, rather than a target) must be actively inhibited (see Liesefeld et al., 2017, for ERP evidence for this sequence of events), so that it no longer competes for selection. The amount of inhibition may either be adjusted to the difficulty of keeping the distractor out of the search, or it may be a fixed amount per capture incident regardless of this difficulty. Future work is required to distinguish between these possibilities.

## Conclusions

Although same-dimension distractors cause four times greater interference than do different-dimension distractors, the

<sup>12</sup> Attentional capture by the distractor may not actually be necessary for target-to-distractor distance effects to manifest. For instance, Gaspar and McDonald (2014) observed a behavioral distance effect (of maximally 55 ms) even though, in their event-related analysis of the EEG, they found no N2pc to the distractor.

probability-cueing effect (i.e., reduced interference by distractors in the frequent vs. the rare region) is evident with both types of distractors. However, the effect is much stronger for same-dimension distractors, which also display a robust target location effect (slower responses to targets appearing in the frequent- vs. the rare-distractor region). The latter is indicative of a strong component of general, spatial suppression of the frequent-distractor region, which we propose operates at the level of the master saliency map, on top of any feature-based modulations. With different-dimension distractors, by contrast, there was a probability-cueing effect but no target location effect. Although the probability-cueing effect is also attributable to an element of differential spatial suppression between the frequent- and rare-distractor regions, this operates at a level prior to the search-guiding master saliency map, selectively down-modulating feature contrast signals from the distractor dimension so that they register only weakly on the master saliency map. The improved ability to suppress distractors in the frequent region appears to be acquired implicitly, without observers being consciously aware of the unequal distractor distribution; though, with very salient distractors, at least some observers may become aware of the unequal distractor distribution and deliberately increase the amount of frequent-region suppression. Given this, open questions for future work concern whether explicit information about the distribution can modulate the effect, whether the present explanatory framework generalizes to other dimensions, and whether possible alternative explanations can be dissociated via direct tracking of attention allocations and suppression mechanisms by means of event-related potentials.

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## Appendix

### Supplementary introduction

When looking for distractor probability cueing, it is important to make sure that there is an effect of statistical learning of spatial cues over and above that of mere intertrial repetitions. For instance, it is known that, in singleton-search episodes, distractor locations are inhibited or negatively tagged, increasing the time it takes for a feature contrast signal at such a location to reach the level of salience required to summon attention (Cepeda, Cave, Bichot, & Kim, 1998; Kumada,

1999; see also Dent, Allen, Braithwaite, & Humphreys, 2012). Thus, given that inhibitory tagging of previous distractor locations is, by definition, more likely in the region where distractors occur frequently, a (subsequent) distractor falling in this region would be more likely to be affected than a distractor in the rare-distractor region—mimicking a learnt probability-cueing effect and thereby reducing distractor interference, when, in fact, the effect is driven purely by (passive) inter-trial dynamics. Goschy et al. (2014) attempted to control for this type of intertrial effect in a dedicated experiment (their Exp. 3) in which the distractor on trial  $n$  ( $D_n$ ) could, by design, not fall on the location of the distractor on trial  $n - 1$  ( $D_{n-1}$ ; intertrial transition  $D_{n-1} - D_n$ ). Goschy et al. indeed found that the differential interference between the frequent- and rare-distractor areas was reduced as a result of ruling out  $D_{n-1} - D_n$  transitions, but a robust effect remained that was attributable to learning of the probability cues. However, changing the design of the experiment (as Goschy et al., 2014, did to exclude distractor location repetitions) may have led to a change in participants' search strategy and thus to a change in the effect sizes. For this reason, we opted for another approach to eliminate inter-trial effects: in the present study, we allowed all possible cross-trial (location) transitions to occur, but partialled out the inter-trial effects by excluding potentially affected trials post-hoc from analysis. A further advantage conferred by this procedure is that it permitted us to quantify the inter-trial effects (i.e., the extent to which they account for the “probability-cueing” effect) within the same experiments (participants) (i.e., without changing the experimental design).

A second caveat concerns examination for the predicted target position effect (in the same-dimension condition). It is thought that when a salient distractor captures attention, it must be (actively) suppressed for focal attention to move on to the next most salient item, the target (see, e.g., Liesefeld et al., 2017), and this suppression affects not only the distractor location itself, but spreads laterally to the surrounding region, tailing off gradually with increasing distance from the distractor location (e.g., Gaspar & McDonald, 2014; Mathôt et al., 2010; Mounts, 2000). Now (with the display arrangement realized in Goschy et al., 2014, and the present study; see Fig. 1), with a distractor in the frequent area, a target in the frequent area would, on average, be nearer to the distractor than a target in the rare area (in the present design as well as that of Goschy et al., 2014, the target–distractor separation around the circle on which the two singletons were arranged varied between one unit [target and distractor adjacent] and four units [target and distractor separated by three intervening stimuli on the circle] when target and distractor were located in the same area, but between two and six units when they were located in different areas). That is, a target in the same area as the distractor would be more likely affected

by lateral inhibition than a target in a different area to the distractor, giving rise to slower reaction times to targets in the frequent as compared to the rare region. Critically, an additional target position effect in the same direction is also predicted by our DWA-based hypothesis for the same-dimension distractor condition.<sup>13</sup> Thus, to remove any confound with this effect in terms of lateral inhibition, analysis must be restricted to (only) such trials for which the target–distractor distance is equated between conditions with a distractor located in the frequent area and those with a distractor in the rare area. In the present study, this was done by restricting analyses to separations of three units ( $9.85^\circ$  of visual angle) and four units ( $12.07^\circ$ ) only (there were too few trials with a separation of two units).

### Supplementary results

As we elaborated above, in order to examine for pure statistical learning effects (here: learning of the distractor frequency distribution), potentially confounding effects—specifically, effects arising from (1) certain intertrial transition effects as well as (2) effects attributable to differential target-to-distractor distances between critical conditions—were eliminated from the data set. Such effects exhibited interesting differential patterns between the same- and different-dimension distractor conditions, as detailed in the following two sections.

**Intertrial effects** A major confound is likely given by (current) trials on which the distractor,  $D_n$ , appears at the location of the last distractor,  $D_{n-1}$ . In such  $D_{n-1}-D_n$  transitions, the current distractor falls on a location that is inhibitorily tagged (as a result of the distractor on the previous trials falling on this position) and is therefore less potent in attracting attention and causing interference. As such transitions are more likely for the frequent- than for the rare-distractor area, they would enhance any differential interference effects between the frequent- and the rare-distractor region that might arise from statistical learning. As indicated by Goschy et al. (2014; comparison of their Exp. 2 with Exp. 1), a significant part of

the differential interference effects between distractors in the frequent versus the rare area is indeed attributable to such  $D_{n-1}-D_n$  transitions. However, other intertrial transitions (besides  $D_{n-1}-D_n$  transitions—the only ones controlled for by Goschy et al., 2014, in their Exp. 3) might affect the magnitude of distractor interference: notably, (1) a (current) target falling at the same position as the previous distractor ( $D_{n-1}-T_n$ ) and (2) a (current) distractor falling at the same position as the previous target ( $T_{n-1}-D_n$ ). Concerning Case 1, given carry-over of inhibitory tagging, a (current) target falling at the same position as the previous distractor would make the current target less potent (i.e., it would take longer to achieve salience and attract focal attention). As instances of type  $D_{n-1}-T_n$  would be much more likely for the frequent-distractor area, this could also skew the results regarding statistical learning of distractor frequency distributions, though in the opposite direction to  $D_{n-1}-D_n$  transitions:  $D_{n-1}-T_n$  transitions would reduce the differential distractor interference between the frequent and the rare area. Concerning Case 2, there is evidence of positive tagging (and carryover) of the target location on a given trial (e.g., Krumeracher et al., 2009). Accordingly, a (current) distractor falling on the previous target location ( $T_{n-1}-D_n$ ) would be more potent, that is, achieve salience faster and thus be more competitive for attracting focal attention. As such instances, too, are more likely for the frequent-distractor area, they would again skew the results: again in the opposite direction to  $D_{n-1}-D_n$  transitions.<sup>14</sup>

All these effects were evident in the present data set. For instance, on distractor-present trials (i.e., on which the current distractor had the potential to produce interference), RTs (to the target) were slower when the target appeared at the same location as the last distractor ( $D_{n-1}-T_n$ ) as compared to a different location (728 vs. 704 ms),  $t(183) = 6.72$ ,  $p < .001$ ,  $d_z = 0.50$ , 95% HPD [17 ms, 33 ms],  $BF_{10} = 3.5 \times 10^7$ , and when a distractor appeared at the same location as the last target ( $T_{n-1}-D_n$ ) as compared to a different location (716 vs. 704 ms),  $t(183) = 3.92$ ,  $p < .001$ ,  $d_z = 0.29$ , 95% HPD [6 ms, 17 ms],  $BF_{10} = 116$ . Finally, RTs (to the target) were faster when the distractor appeared at the same location as the last distractor ( $D_{n-1}-D_n$ ), as compared to a different location (693 vs. 704 ms),  $t(183) = -4.34$ ,  $p < .001$ ,  $d_z = .32$ , 95% HPD [-15 ms, -5 ms],  $BF_{10} = 575$ .

Interestingly, these intertrial effects differed between the two distractor types. An ANOVA with the factors inter-trial transition type (no location repetition,  $D_{n-1}-T_n$ ,  $D_{n-1}-D_n$ ,  $T_{n-1}-D_n$ ,  $T_{n-1}-T_n$ ) and distractor type (same-dimension vs. different-dimension) revealed, besides main effects of distractor type,  $F(1, 182) = 44.52$ ,  $p < .001$ ,  $\eta_p^2 = .20$ , and intertrial

<sup>13</sup> Note, however, that according to the DWA the additional spatial effect should occur exclusively for same-dimension, not for different-dimension, distractors, and it should occur even for distractor-absent trials, on which no distractor in the display would need to be inhibited in order for focal attention to be allocated to the target. The lateral-inhibition effect, by contrast, would occur equally with same- and with different-dimension distractors, but only on distractor-present, not on distractor-absent, trials. Furthermore, with a distractor in the rare area, a target in the rare area would, on average, be nearer to the distractor than a target in the frequent area and thus be more affected by lateral inhibition. Although this would again predict a target position effect (RTs to rare-area targets being slower than RTs to frequent-area targets), the effect is actually in the opposite direction from that predicted by the DWA-based account. By the latter account, RTs to frequent-area targets should be generally slower than RTs to rare-area targets, even on distractor-absent trials, and no matter whether the distractor was located in the frequent or the rare region on target-present trials.

<sup>14</sup> Note that target location repetitions across successive trials ( $T_{n-1}-T_n$ ) were balanced between the frequent and rare distractor areas; accordingly, such repetitions should not impact any differential distractor interference effects between the frequent and rare regions.

transition,  $F(4, 728) = 110.47, p < .001, \eta_p^2 = .38$ , the interaction to be significant,  $F(4, 728) = 18.01, p < .001, \eta_p^2 = .09$ . In follow-up  $t$  tests, the RTs of the four inter-trial repetition conditions were contrasted with the “no-repetition” baseline separately for different and same-dimension distractors. For *different-dimension* distractors, as compared to the baseline (668 ms), RTs were slightly slowed, by a little over 10 ms, to targets appearing at a previous distractor location ( $D_{n-1}-T_n$ : 681 ms),  $t(127) = 3.50, p < .001, d_z = 0.31, 95\%$  HPD [6 ms, 20 ms],  $BF_{10} = 31$ , or when the current distractor appeared at a previous target location ( $T_{n-1}-D_n$ : 680 ms),  $t(127) = 4.14, p < .001, d_z = 0.37, 95\%$  HPD [7 ms, 19 ms],  $BF_{10} = 263$ . There was little facilitation ( $-2$  ms) when the current distractor appeared at the previous distractor location ( $D_{n-1}-D_n$ : 666 ms),  $t(127) = -0.46, p = .644, d_z = .04, 95\%$  HPD [ $-6$  ms, 5 ms],  $BF_{10} = 0.11$ , but substantial facilitation ( $-49$  ms) when the current target appeared at the previous target location (619 ms),  $t(127) = -11.08, p < .001, d_z = .98, 95\%$  HPD [ $-57$  ms,  $-40$  ms],  $BF_{10} = 2.21 \times 10^9$ . For *same-dimension* distractors, as compared to the baseline (789 ms), RTs were substantially slowed, by over 50 ms, when the current target appeared at the previous distractor location ( $D_{n-1}-T_n$ : 842 ms),  $t(55) = 6.85, p < .001, d_z = .91, 95\%$  HPD [37 ms, 69 ms],  $BF = 1,795,702$ , whereas there was relatively little slowing (9 ms) when the current distractor appeared at the previous target location ( $T_{n-1}-D_n$ : 798 ms),  $t(55) = 1.35, p = .182, d_z = 0.18, 95\%$  HPD [ $-5$  ms, 22 ms],  $BF_{10} = 0.34$ . We observed sizeable facilitation ( $-32$  ms) when the current distractor appeared at the previous distractor location ( $D_{n-1}-D_n$ : 757 ms),  $t(55) = -6.69, p < .001, d_z = 0.89, 95\%$  HPD [ $-40$  ms,  $-21$  ms],  $BF_{10} = 1,019,639$ , and even greater facilitation ( $-70$  ms) when the current target appeared at the previous target location ( $T_{n-1}-T_n$ : 719 ms),  $t(55) = -8.08, p < .001, d_z = 1.08, 95\%$  HPD [ $-85$  ms,  $-50$  ms],  $BF_{10} = 1.54 \times 10^8$ . Thus, the interaction effect derives from the fact that especially the (inter-trial) distractor location inhibition ( $D_{n-1}-T_n$  trials: 53 vs. 13 ms;  $D_{n-1}-D_n$  trials:  $-32$  vs.  $-2$  ms), and to some extent also the target location facilitation (at least on  $T_{n-1}-T_n$  trials:  $-49$  vs.  $-70$  ms), was greatly increased in the same-dimension relative to the different-dimension condition (distractor location inhibition was increased by a factor of at least 4).

As we already said, location transitions involving the distractor happened more often in the frequent-distractor area (therefore confounding the results). On average across participants, a target appeared at the same location as the previous distractor absolutely more often in the frequent ( $N = 30$ ) than in the rare ( $N = 4$ ) distractor region; a distractor appeared at the same location as the previous distractor much more often in the frequent ( $N = 59$ ) than in the rare ( $N = 1$ ) distractor region; also, a distractor appeared in the same location as the previous target absolutely (and

relatively somewhat) more often in the frequent-distractor region ( $N = 39$ ) than in the rare-distractor region ( $N = 4$ ). Given their distribution imbalances, all these intertrial transitions should be—and, in the present study, were—excluded from the analysis of “pure” statistical learning effects.<sup>15</sup>

**Target-to-distractor distance effects** Another confound in the present study may be that targets are subject to differential amounts of lateral inhibition (arising from the suppression of distractors that captured attention) depending on whether they are located within the same area as the distractor (i.e., both in the frequent- or the rare-distractor area, in which case the average distance of the target to the distractor would be smaller and therefore the inhibitory influence larger) or in different areas (in which case the average distance would be larger and therefore the inhibitory influence smaller). Such lateral-inhibition effects could conceivably add to (distractor in frequent area) or take away from (distractor in rare area) the target position effect predicted on the DWA-based account—though only under distractor-present conditions.

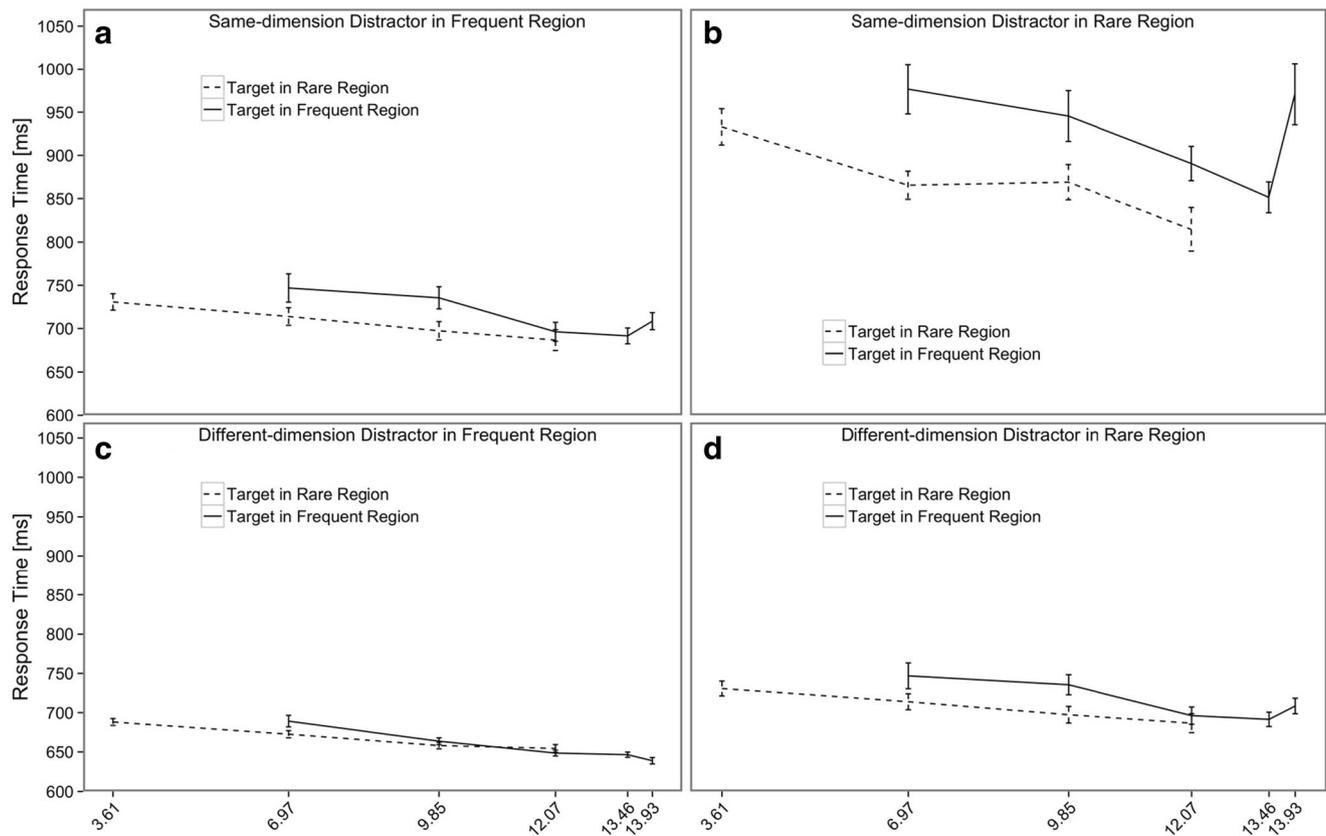
For the present data, the lateral-inhibition effects are depicted in Fig. 4. Each panel presents RT as a function of the distance (in degrees of visual angle) of the target from the distractor, separately for targets located in the frequent-distractor area and targets located in the rare-distractor area; these functions are shown separately for same- and different-dimension distractors (upper and lower panels) appearing in the frequent- and rare-distractor areas (left and right panels), respectively. As can be seen from the (fairly linear) decreases in RTs with increasing target-distractor separation, lateral-inhibition effects did manifest in all conditions.<sup>16</sup> Furthermore, the amount of lateral inhibition, measured in terms of the rate of RT decrease per unit of distance (i.e., degrees of visual angle), appears overall more marked for same-dimension than for different-dimension distractors ( $-12.99$  ms/deg vs.  $-4.72$  ms/deg),  $t(72.73) = -6.1, p < .001, d_z = 1.18, 95\%$  HPD [ $-9.897$  ms/deg,  $-7.582$  ms/deg],  $BF_{10} = 1.193e + 09$ .<sup>17</sup>

To make sure that we compared like with like in the critical analyses of distractor interference effects, we went on to examine RTs as a function of Distractor Location

<sup>15</sup> Note that, in the present study, the results remained similar after removal, which occurred because the two effects of distractor-distractor transitions ( $D_{n-1}-D_n$ ) facilitating processing and distractor-target transitions ( $D_{n-1}-T_n$ ) impairing processing (in the frequent area) largely canceled each other out. Also note that target-target ( $T_{n-1}-T_n$ ) transitions do not affect the probability-cueing effect, because such transitions are equally likely in both (the frequent and the rare) distractor areas.

<sup>16</sup> This pattern was consistent across the range of distances for conditions with a distractor in the frequent area, for which we have relatively reliable estimates. The one deviant value, for the greatest separation with a same-dimension distractor in the rare area and a target in the frequent area, is likely attributable to a measurement error, given the few trials available for this extreme, distractor-in-rare-area condition.

<sup>17</sup> Slopes were calculated excluding the most extreme distance of 13.93°.



**Fig. 4** Mean response times as a function of target-to-distractor distance (in degrees of visual angle), for each of the combinations of Distractor Location (distractor located in frequent vs. rare region: left- vs. right-hand

panels) × Target Location (target located in frequent- vs. rare-distractor region), separately for the two distractor types (same- vs. different-dimension: upper vs. lower panels).

(distractor in frequent vs. rare area) × Target–Distractor Distance (9.85° vs. 12.07°) × Target Position (same vs. opposite area with respect to distractor). The latter variable was included as, conceivably, the gradient of the inhibition applied might differ between the two distractor areas—in which case lateral inhibition would vary even for equivalent distances. Distractor Location × Distance × Target Position (repeated measures) ANOVAs performed separately for same- and different-dimension distractors failed to reveal any interactions between target position and distance (Target Position × Distance:  $F(1, 47) = 0.71$  and, respectively,  $F(1, 89) = 0.02$ ,  $ps > .1$ ; Distractor Location × Target Position × Distance:  $F(1, 47) = 0.04$  and, respectively,  $F(1, 89) = 1.22$ ,  $p = .272$ ).<sup>18</sup> That is, there was no evidence of modulation of any target position effects by distractor-to-target distance [the main effect of target position was significant for the same-dimension, but not for the different-dimension condition:  $F(1, 47) = 11.29$ ,  $p = .002$ , vs.  $F(1, 89) = 0.30$ ,  $p = .585$ ]. Restated, for equivalent distractor-to-target distances (and for a given type of

distractor appearing in a given area), target position effects, if any, are simply additive to the lateral-inhibition effects. Thus, by including in the analysis of target position effects only “equated” distances, we can be confident that any effects on target processing revealed are not confounded by differential amounts of lateral inhibition when the target is located within the same versus the opposite area to the distractor.

Accordingly, prior to analysis of the distractor interference effects reported below, we dealt with (potential) *intertrial transition confounds* by eliminating all trials on which (1) the current distractor appeared at the exact same position as the previous distractor ( $D_{n-1}-D_n$ ); (2) the current target appeared at the exact same position as the previous distractor ( $D_{n-1}-T_n$ ); and (3) the current distractor appeared at the exact same position as the previous target ( $T_{n-1}-D_n$ )—which resulted in the removal of 17% of the trials. Furthermore, to deal with *lateral-inhibition confounds*, we only included (distractor-to-target) distances in the analysis that were common to the conditions with targets in the frequent-distractor area and targets in the rare-distractor area—specifically, distances of 9.85°, and 12.07°, for all Distractor Type × Distractor Position combinations. The latter two distances were included

<sup>18</sup> Due to missing values, the number of observers that could be entered into these analyses was reduced from 56 to 48 in the same-dimension distractor condition, and from 128 to 90 in the different-dimension condition.

because missing values were minimal at these distances (only one participant had to be excluded) and the distances could be effectively equated between the target-in-frequent-distractor-area and target-in-rare-distractor-area conditions. Including only these two, equated distances in the distractor interference analysis led to the omission of a further 26% of the trials.

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