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Distractor-Interference Reduction Is Dimensionally Constrained

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Abstract

The dimension-weighting account predicts that if observers search for a target standing out from the background in a particular dimension, they cannot readily ignore a distractor standing out in the same dimension. This prediction is tested here by asking two groups of observers to search for an orientation target or a luminance target, respectively, and presenting an additional distractor defined in either the respectively same dimension or the other dimension. Notably, in this cross-over design, the physically identical distractors served both as same- and different-dimension distractors, depending on target condition. While same-dimension distractors gave rise to massive interference, different-dimension distractors caused much weaker (though still substantial) interference. This result is most readily explained by the dimension-weighting account: different-dimension distractors are considerably down-weighted but not fully suppressed. Furthermore, same- and different dimension distractors delayed response times even when considering only the fastest (down to 2.5%) of trials, indicating that interference is exerted consistently on each trial, rather than probabilistically on some trials. Our results put strong constraints on models of distractor handling in visual search.

Keywords. attentional capture, distractor handling, dimension-weighting account, additional-singleton task, visual search

Distractor-Interference Reduction Is Dimensionally Constrained

Objects that stand out from the environment – i.e., that are salient – tend to attract attention, even if they are irrelevant to the task at hand. Given the severe limitation in attentional resources, such distraction can be harmful, because attending to an irrelevant object (distractor) could mean that a relevant object (target) is found and acted upon only later or missed altogether. Fortunately, powerful mechanisms have evolved to avoid or reduce interference by distractors. One such mechanism is implied by the Dimension Weighting Account (DWA): The core assumption of the DWA is that top-down influences (i.e., voluntary control or search history) can bias the visual system to preferentially process objects that stand out from the environment in one particular, target dimension – whereby the impact of salient objects that stand out in any other dimension is reduced. The dimensional constraint is crucial: it implies that it is not possible to exclusively process a particular feature; rather, any feature – whether target or distractor – within the target dimension receives some advantage in the competition for attentional resources (Found & Müller, 1996; Müller, Heller & Ziegler, 1995; Müller, Reimann, & Krummenacher, 2003; Zehetleitner, Goschy, & Müller, 2012; for recent reviews, see Liesefeld, Liesefeld, Pollmann, & Müller, in press; Liesefeld & Müller, under revision).

Indeed, using the N2pc (indicating attentional allocation/selection; Eimer, 1996; Luck & Hillyard, 1994a,b) and P_D components (indicating attentional suppression/disengagement; Hickey, Di Lollo, & McDonald, 2009; Sawaki, Geng, & Luck, 2012; Toffanin, de Jong, & Johnson, 2011) of the event-related potential, Liesefeld, Liesefeld, Töllner, and Müller (2017) recently showed that a distractor standing out from the environment in the same dimension as the target (*same-dimension distractor*; a 45°-tilted distractor and 12°-tilted target among vertical non-targets) inevitably captures attention (see also Schubö & Müller, 2009). The distractor was suppressed and the target processed only *after* attention was first misallocated towards the distractor. Furthermore, response times were delayed by 225 ms when the same-dimension distractor was present. In contrast, when the distractor is defined in a different dimension to the target (*different-dimension distractor*) and the target remains the same across trials (thus allowing the build-up of an effective weight set; see Burra & Kerzel, 2013), the distractor is typically not attended, but suppressed before it can capture attention (Jannati, Gaspar, & McDonald, 2013; Töllner, Müller, & Zehetleitner, 2012) and the effect of distractor presence on response times is tiny in comparison (interference effects of 5 to 25 ms; e.g., Jannati et al., 2013; Theeuwes, 1992; Töllner et al., 2012). Sauter, Liesefeld, Zehetleitner, and Müller (2018) were – to our knowledge – the first to directly compare interference by a same- versus a different-dimension distractor. Observers searched for an orientation singleton (12°-tilted target) and one group had to ignore a red distractor (different-dimension distractor), while the other group had to ignore a 90°-tilted distractor (same-dimension distractor). In line with the DWA, interference was high in the same-dimension distractor group and low in the different-dimension distractor group (94 ms vs. 14 ms; see also Chan & Hayward, 2014; Kumada, 1999; Zehetleitner et al., 2012).

All this is exactly as predicted by the DWA: when observers can set themselves for a particular target-dimension, a distractor causes strong interference only if it is defined in the same dimension as the target (see the Discussion section for in-depth comparisons with various alternative accounts). Also note that the DWA does not necessarily predict that different-dimension distractors are fully ignored: while it is advantageous to reduce the influence of distractors, it also makes sense from an evolutionary perspective to keep an “open eye” for unexpected events. A good compromise between these two goals can be achieved by setting the weights so that signals from distractor dimensions are dampened but not fully cancelled (see Müller et al., 1995, p. 15; Müller & Krummenacher, 2006, p. 499). In this case, different-dimension distractors of low salience can be effectively ignored, while a highly salient (and therefore potentially behaviourally relevant) different-dimension distractor would still have the potential to attract attention. This would explain why interference is much lower with different-dimension, compared to same-dimension distractors, but not fully cancelled.

Other accounts of attentional capture encounter difficulties in explaining the Liesefeld et al. (2017) and Sauter et al. (2018) data. If observers were able to adopt a relatively precise (i.e., feature-specific) attentional set (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992, 1993) or target template

(Olivers Peters, Houtkamp, & Roelfsema, 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008), same-dimension distractors should not match that set or template and thus interfere only little with search for the target. The same applies to the idea of feature-based salient-signal suppression (Gaspar, & McDonald, 2014; Gaspelin, Leonard, & Luck, 2015, 2017; Gaspelin & Luck, 2018a,b): if participants were able to selectively suppress a specific distractor feature, they should be able to suppress a 90° (i.e., horizontal) distractor in Sauter et al. (2018) or a 45° distractor in Liesefeld et al. (2017) during search for a target tilted by 12° (into the opposite direction with respect to distractor tilt), because target and distractor features stayed constant throughout the experiment and were therefore perfectly predictable. Also the hypothesis that salient distractors capture attention in a purely bottom-up fashion (Theeuwes, 1991, 1992, 2010) cannot readily explain why, in Liesefeld et al. (2017), the same-dimension distractor interfered so massively (indicative of reliable capture) compared to prior studies in the literature (which typically use highly salient different-dimension distractors), and why the same-dimension distractor (a 90° tilted bar) in Sauter et al. (2018) induced so much more interference than the different-dimension distractor (a red bar), assuming that both types of distractors were of comparable saliency.

Critically, although the distractors in Sauter et al. (2018) were both highly salient, we cannot fully exclude the possibility that the same-dimension distractor was somewhat more salient than the different-dimension distractor and that this (likely small) difference might explain the (large) difference in interference strength (due to some non-linear relationship between saliency and interference strength). The present study therefore provides a more direct test of the DWA predictions regarding distractor handling that is lacking so far: a *physically identical* distractor should cause strong or weak interference depending on the current weight settings. A major advantage of testing this particular prediction is that, in contrast to previous studies, we can be perfectly sure that the bottom-up saliency of the distractor does not vary between same-dimension and different-dimension distractor conditions, because it is the exact same stimulus that fulfils both roles and only the top-down weight settings change between conditions.

To experimentally manipulate the weight settings and as illustrated in Figure 1, we had one group of observers search for an orientation-defined target (a 12°-tilted bar among vertical bars) and another group for a luminance-defined target (a 59%-intensity bar among 27%-intensity bars). Thus, the former group was assumed to up-weight signals from the orientation dimension and the latter signals from the luminance dimension. To probe this differential up-weighting, both groups of observers were additionally exposed to physically identical orientation (45°-tilted) and luminance (98%-intensity) distractors, with distractor presence (present vs. absent) and distractor type (45°-tilted vs. 98% intensity) unpredictably intermixed across trials. Thus, the 45°-tilted distractor was a same-dimension distractor for the orientation-target group and a different-dimension distractor for the luminance-target group; and the 98%-intensity distractor was a same-dimension distractor for the luminance-target group and a different-dimension distractor for the orientation-target group. As predicted, the 45°-tilted distractor caused massive interference when observers were searching for an orientation target and relatively weak interference when observers searched for a luminance target, and vice versa for the 98%-intensity distractor (i.e., strong interference in the luminance target group and weak interference in the orientation target group).

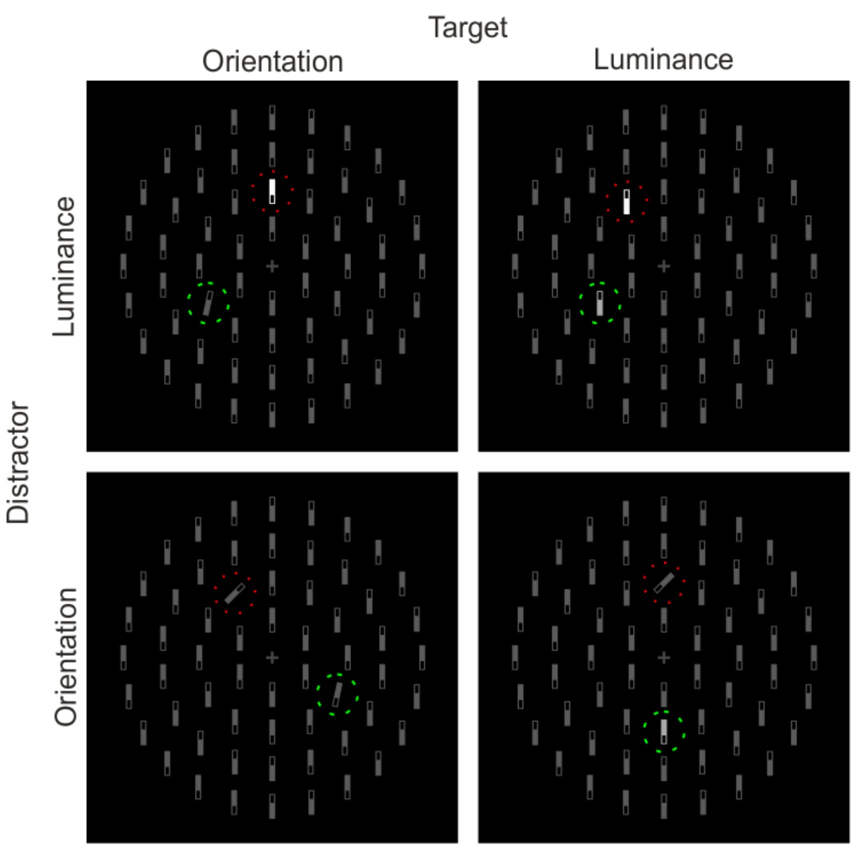

Figure 1. Search displays employed in the present task. For purposes of illustration, targets are marked by green dashes and distractors are marked by red dots; these markers were not present in the actual search displays. Different groups of observers had to find a bar tilted 12° to the right (displays on the left) or a bar slightly brighter than the

homogenous non-targets (59% instead of 27% intensity; displays on the right) and to indicate the position of the notch (top or bottom) in the target bar. On some trials, the displays additionally contained a 98%-intensity (luminance) distractor (upper displays) or a 45°-tilted (orientation) distractor (lower displays). Targets and distractors always appeared at a position on the second ring from fixation. Distractors were always completely irrelevant and therefore, ideally, to be ignored.

Methods

Participants. Twenty-four right-handed students recruited at Ludwig-Maximilians-Universität participated in this study. Of these, 12 searched for an orientation target (median age: 23 years, range: 20-32 years, 9 female) and 12 searched for a luminance target (median age: 22 years, range: 18-35 years, 10 female). All participants had normal or corrected to normal vision. They gave prior informed consent (in writing) and received course credit or were paid for their participation.

Stimuli. Stimuli were grey or white bars (0.18 × 0.81°) presented on a TFT monitor (screen resolution: 1,920 × 1,080 pixels; refresh rate: 60 Hz), at a viewing distance of approximately 60 cm, against a black background (slightly lighter for the luminance-target group than for the orientation-target group, owing to a mistake during copying the settings). Search displays (Fig. 1) consisted of 60 bars arranged around four concentric rings (with radii of 1.1°, 2.2°, 3.3°, and 4.4°, respectively) centred on a central grey fixation cross (0.49°). Each bar contained a notch (~0.25° in height) in its upper or lower part. Most of the bars (homogenous background/non-targets) were oriented vertically (0°) and at 27% (of maximum) intensity. The target was either tilted by 12° to the right and at non-target intensity (orientation-target group), or it was brighter than the non-targets (59% intensity) and vertical. The orientation distractor was tilted 45° to the right and at non-target intensity; the luminance distractor was at 98% intensity and vertical.

Design and procedure. Participants performed a classification-search task in which they had to find a target bar that was either tilted 12° to the right or at 59% intensity and to press a mouse button with either their right or left thumb indicating the position of the notch in the target bar (response-button assignment counterbalanced across participants). Targets (and distractors) were always presented on the second ring (from fixation). The search display was shown until response, which had to be issued within 4 s (response deadline). Participants were told to respond as fast as possible without sacrificing accuracy. In case of an incorrect or delayed response, the fixation cross changed colour for 1,000 ms, turning red if the answer was wrong and blue if it was too slow. The intertrial interval contained only the fixation cross and was jittered between 0.8 and 1.6s. Participants of each group performed 48 (non-analysed) training trials without response deadline followed by 24 blocks of 48 trials each, thus yielding 1152 analysed trials in total with 384 trials per condition (randomly intermixed and balanced per block; same-dimension distractor vs. different-dimension distractor vs. distractor absent; i.e. each distractor type occurred on 1/3 of trials).

Analyses. For analyses of mean RTs, we excluded trials with incorrect responses and trials with log-transformed RTs 1.5 times the interquartile difference above the third or below the first quantile of the respective distribution (separately for each participant and condition). Time-outs (i.e., no response within 4s post search display onset) were excluded from all analyses. For ANOVAs, *p* values are Greenhouse-Geisser corrected were appropriate. All *t* tests are reported one-tailed with the directed hypotheses that the presence of any distractor delays (rather than speeds) response times and that same-dimension distractors cause a stronger delay than different-dimension distractors (rather than vice versa). To further explore the differential effects between same-dimension and different-dimension distractors, we additionally analysed (correct) response-time quantiles extracted as described by Heathcote, Brown, and Mewhort, 2002 (for examples and discussions of how analysing response-time distributions and quantiles in particular can provide valuable information beyond mean response times, see, e.g., Liesefeld et al., 2016; Liesefeld, Liesefeld, Müller, & Rangelov, 2017; Miller, 1982; Moran, Zehetleitner, Müller, & Usher, 2013; Ulrich, Miller, & Schröter, 2007; Wolfe, Palmer, & Horowitz, 2010; but see Leber, Lechak, & Tower-Richardi, 2013, for potential pitfalls).

Results

The following analyses start with a test for possible group differences, before examining the distractor effects of interest. There was a main effect of group on RTs (Fig. 2A) that approached significance, $F(1,22) = 3.58$, $p = .072$, $\eta_p^2 = .14$; a significant main effect of group on error rates (Fig. 2B), $F(1,22) = 9.44$, $p = .006$, $\eta_p^2 = .30$; and an interaction between group and distractor condition on error rates (Fig.

2B), $F(2,44) = 7.32$, $p_c = .007$, $\eta_p^2 = .25$. The interaction was not significant for RTs (Fig. 2A), $F(2,44) = 0.21$, $p_c = .763$, $\eta_p^2 = .01$. The main effect of group pointed in opposite directions for RTs and error rates (faster RTs and higher error rates in the luminance-target group), thus potentially indicating differential speed-accuracy tradeoffs between the two groups, rather than differences in the actual performance level (Heitz, 2014; Luce, 1986; Pachella, 1974). To test for this possibility, we combined speed and error rates in a way that controls for speed-accuracy tradeoffs (Balanced Integration Score, BIS, calculated across both target groups and all distractor conditions; Liesefeld, Fu, & Zimmer, 2015; Liesefeld & Janczyk, 2018). Indeed, the main effect of group vanished with the BIS transformation, $F(1,22) = 0.81$, $p = .379$, $\eta_p^2 = .04$, but the interaction remained, $F(2,44) = 7.86$, $p_c = .005$, $\eta_p^2 = .26$. As can also be seen from Figure 2B, this interaction mainly reflects a weaker interference effect on error rates for both types of distractors in the orientation-target condition. Given that error rates were very low in the orientation-target group (2.1% on average for the same-dimension distractor), this is most likely a floor effect. Of note, this interaction is not driven by a condition-specific speed-accuracy tradeoff, as the numerical pattern regarding this interaction is in the same direction in RTs and error rates.

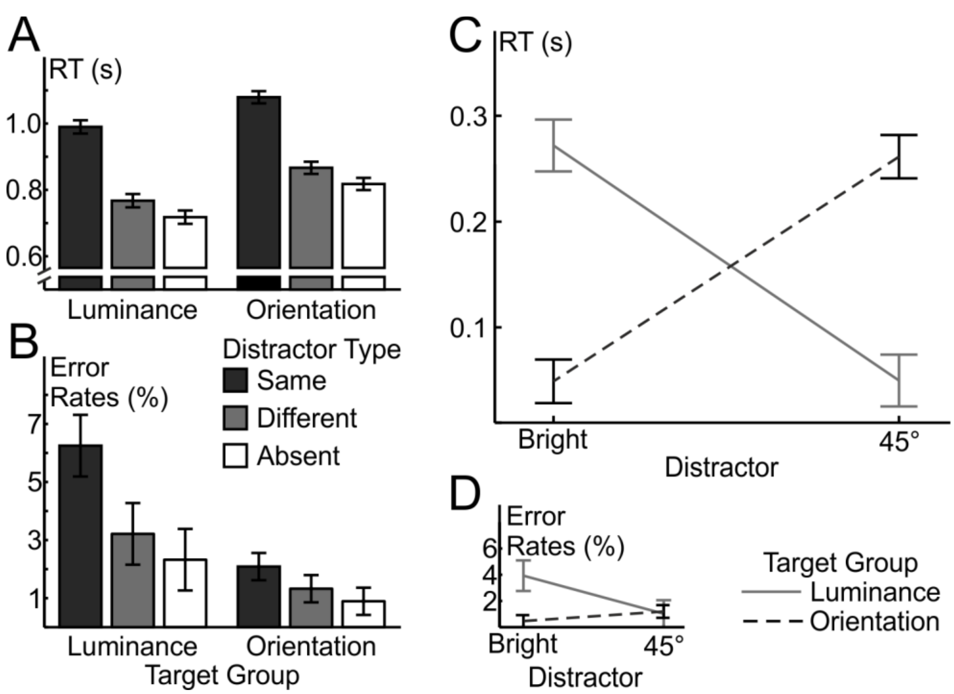

Figure 2. Distractor-interference effects on average RTs (A and C) and error rates (B and D). A and B display data for each condition and C and D display the extracted interference effect (distractor-present minus distractor absent). The main effect of interest is displayed in panel C: The physically identical distractor causes either high or low

interference depending on whether observers are currently searching for a target defined in the same or a different dimension. Error bars indicate 95% within-subject confidence intervals for the main effect of distractor type in the respective group (Jarmasz & Hollands, 2009; Loftus & Masson, 1994).

Our main research question was whether the physically identical distractor would cause much higher interference during search for a target defined in the same versus a different dimension. Higher interference by same-dimension distractors is predicted by the DWA, because people should be able to selectively down-weight distractors from a different dimension, whereas any attempt to down-weight a distractor from the same dimension would inevitably also down-weight the target and thus be counterproductive with respect to the goal of finding and responding to the target. As can be seen from Figure 2C, the result pattern perfectly confirms this hypothesis: the 45°-orientation distractor caused high interference in the orientation-target group (261 ms), $t(11) = 18.87$, $p < .001$, $d_z = 5.45$, and low interference in the luminance-target group (50 ms), $t(11) = 5.90$, $p < .001$, $d_z = 1.70$, as measured by response times. Conversely, the bright luminance distractor caused high interference in the luminance-target group (272 ms), $t(11) = 18.36$, $p < .001$, $d_z = 5.30$, and low interference in the 12°-orientation-target group (49 ms), $t(11) = 4.98$, $p < .001$, $d_z = 1.44$. The same pattern was evident in the error rates, with a strong increase in error rates for same-dimension distractors (orientation-target group: 1.2%, $t(11) = 3.16$, $p = .005$, $d_z = 0.91$; luminance-target group: 3.9%, $t(11) = 4.45$, $p < .001$, $d_z = 1.28$) and weak increases for different-dimension distractors (orientation-target group: 0.4%, $t(11) = 1.78$, $p = .051$, $d_z = 0.52$; luminance-target group: 0.9%, $t(11) = 2.64$, $p = .011$, $d_z = 0.76$). Directly comparing the interference effect for same-dimension and different-dimension distractors (Fig. 2C) shows that response times are significantly more delayed for same-dimension distractors in both the orientation target group, $t(11) = 16.09$, $p < .001$, $d_z = 4.64$, and the luminance target group, $t(11) = 14.10$, $p < .001$, $d_z = 4.07$. Also, error rates (Fig. 2B and D) were significantly higher for same- compared to different-dimension distractors in both groups, $t(11) = 2.45$, $p = .016$, $d_z = 0.71$, and $t(11) = 4.05$, $p = .001$, $d_z = 1.17$, respectively.

Quantile analysis

The weaker effect for different-dimension distractors might emerge because a different-dimension distractor captures attention less often and, as a result, fewer capture trials would go into each averaged response time than for same-dimension distractors. Alternatively, both distractors exert interference on (almost) every trial (see Liesefeld et al., 2017) and the amount of interference per trial differs between distractors. In the former case (*sporadic capture*), the interference should be similar for same- and different-dimension distractors on slow-response trials (higher quantiles) and absent for different-dimension distractors on fast-response trials (lower quantiles). In the latter case (*consistent interference*), the amount of interference should differ between same-dimension and different-dimension distractors throughout all quantiles and all quantiles should show evidence of interference effects. A rather fine-grained quantile analysis is possible with the current data set, as we collected a relatively large number of 348 trials per condition.

We first analysed quantiles 0.1, 0.3, 0.4, 0.5, 0.7, and 0.9 (see Figure 3). In line with consistent interference, for the luminance-target group and the orientation-target group, interference was present at each quantile for different-dimension distractors (all ts > 3.97, all ps < .002, all ds > 1.14) as well as same-dimension distractors (all ts > 9.34, all ps < .001, all ds > 2.69). Furthermore, the difference in interference between same- and different-dimension distractors was significant for each quantile (all ts > 6.50, all ps < .001, all ds > 1.87).

As evident in Figure 3, the interference effect increases with quantile for same- and different-dimension distractors. Main effects of quantile were significant for both distractors in both groups, all $F(4,44)$s > 12.39, all p_cs < .001, all $\eta_p^2 > 0.52$. The effect was stronger for same-dimension than for different-dimension distractors, as indicated by significant Distractor-Type × Quantile interactions, $F(4,44) = 25.37$, $p_c < .001$, $\eta_p^2 = .70$, and $F(4,44) = 21.03$, $p_c < .001$, $\eta_p^2 = .66$, for the orientation target and the luminance target group, respectively. This (differential) increase in the interference effect with quantile might simply mean that the degree of distractor interference is not a fixed value, but varies across trials (with those trials featuring larger effects tending to end up in the higher quantiles), and that the variance is larger in the same-dimension than in the different-dimension distractor-interference effect (see Leber et al., 2013, for various potential sources of this differential variance).

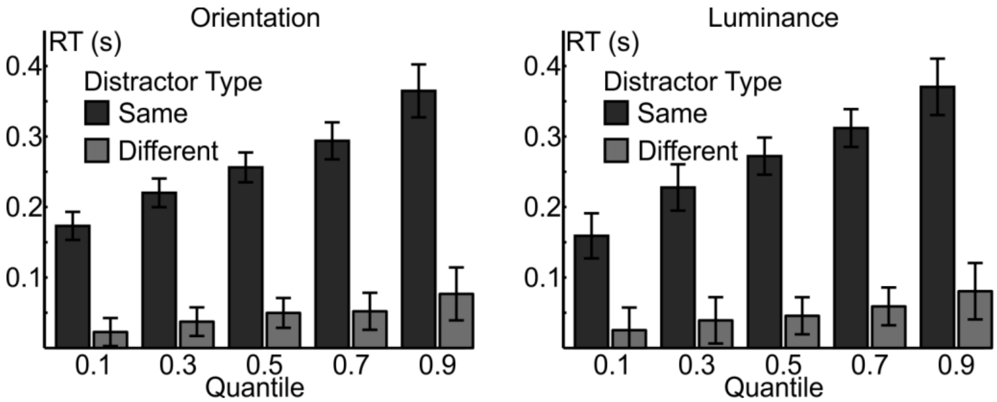

Figure 3. Same- and different-dimension-distractor effects as a function of quantile (10% - 90% of fastest trials) for the orientation- and luminance-target groups. Throughout all quantiles, distractor interference was present for different- as well as same-dimension distractors and the effect was stronger for same- compared to different-dimension distractors. Error bars indicate 95% within-subject confidence intervals for the main effect of distractor type (Jarmasz & Hollands, 2009; Loftus & Masson, 1994).

To establish down to which point interference effects persist, we further analysed quantiles below 0.1 in steps of .005. For different-dimension distractors, interference was significant down to quantile 0.025 in the orientation-target group, $t(11) = 1.94$, $p = .039$, $d_z = 0.56$, and down to quantile 0.01 in the luminance-target group, $t(11) = 3.14$, $p = .005$, $d_z = 0.91$. For same-dimension distractors, interference was significant down to quantile 0.005 (the lowest quantile analysed) in the orientation-target group, $t(11) = 6.73$, $p < .001$, $d_z = 1.94$, and the luminance-target group, $t(11) = 5.63$, $p < .001$, $d_z = 1.63$. The difference in interference was significant down to quantile 0.005 as well, in the orientation-target group, $t(11) = 6.29$, $p < .001$, $d_z = 1.82$, and the luminance-target group, $t(11) = 3.89$, $p = .001$, $d_z = 1.12$. That is, most effects were present even in the 0.5% of fastest trials.

Discussion

As predicted on the Dimension-Weighting Account (DWA), same-dimension distractors caused substantially more interference than different-dimension distractors. Given that physically identical distractors caused massive interference when observers were searching for a target defined in the same dimension and only weak interference when searching for a target defined in a different dimension, this finding cannot be explained by the stimuli’s respective saliencies. Instead, we must assume a goal-related, top-down influence to explain this pattern of results. Most likely, the visual system was tuned to process orientation-singletons in the orientation target group and to process luminance-singletons in the luminance target group. Of note, observers were apparently unable to specifically set themselves for a particular orientation (12°) or for a particular luminance level (59% intensity). Instead, this tuning was dimensionally constrained in that any orientation signal was amplified when searching for an orientation target and any luminance signal was amplified when searching for a luminance target.

Dimensional constraints on search modes/attentional sets

Bacon and Egeth (1994) showed that observers can adopt either of two search modes (see also Egeth, Leonard, & Leber, 2010; Leber & Egeth, 2006): *singleton-detection mode*, in which any salient object attracts attention, versus *feature-search mode*, in which only the sought-after feature will attract attention. The strong same-dimension distractor interference observed in the present study could be explained by assuming that observers adopted a singleton-detection mode. The weak interference by the different-dimension distractor could be explained by observers adopting a feature-search mode. Although it would explain the two results in isolation, the problem with this interpretation is that the two modes are mutually exclusive and that same-dimension and different-dimension distractors were unpredictably intermixed in the present study so that contingent switching between the two modes was not possible. Instead, the present results are more in line with an intermediate, dimension-based search mode, which is simply another way of saying that the whole target dimension was up-weighted, as assumed by the DWA.

Relatedly, the contingent-capture hypothesis (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992, 1993; Lien, Ruthruff, Goodin, & Remington, 2008) assumes that only distractors that match the current *attentional set* (sometimes referred to as *search/attentional template*; Olivers, Peters, Houtkamp, & Roelfsema, 2011) will capture attention. According to this theory, our results demonstrate that the attentional set of our observers comprised either both orientation singletons (orientation target *and* orientation distractor) or both luminance singletons (luminance target *and* luminance distractor) and that they did not restrict their attentional set to the respective specific target feature (for evidence of an attentional set comprising the whole colour dimension, see Folk & Anderson, 2010; Folk & Remington, 1998; Harris, Becker, & Remington, 2015).

There are two potential reasons why observers did not adopt a feature-search mode/did not restrict their attentional set to the target feature in our study: they were either unable or unwilling to do so. The DWA posits that feature weighting is hierarchically constrained, so that observers are unable to set themselves for or against a specific feature within a given dimension without influencing the weights for the whole dimension accordingly (see, e.g., Müller et al., 2003, with regard to top-down set in response to dimension and feature cues, and Zehetleiter et al., 2012, with regard to distractor suppression in singleton-detection and feature-search mode). The alternative, however, remains that observers were unwilling to restrict their set accordingly, potentially because operating in feature-search mode is more effortful, requiring a greater degree of cognitive control, compared to a dimension-search mode (see, e.g., Egeth et al., 2010; Irons & Leber, 2016; Leber & Egeth, 2006; Zehetleiter et al. 2012, regarding efficacy/effort tradeoffs in visual search). Potentially, people have various search strategies (e.g., singleton-detection, feature-search, and dimension-weighting) at their disposal, and choose among them in a way that (subjectively) maximizes task performance while minimizing effort. Our results would then indicate that dimension weighting was most efficient in the present task design. Note that the possibility of observers adopting a feature set under certain conditions is not inconsistent with the DWA: DWA does allow for the possibility of feature-specific top-down weighting in visual search, where, critically however, feature weighting is assumed to be constrained by superordinate dimension weighting.

Even with this somewhat weaker alternative interpretation of our findings, the dimension-search mode is still of high importance, because this is the mode observers would usually adopt. Given that our participants did not adopt a feature-search mode even though searching for a specific target feature would have helped them ignore the very potent same-dimension distractor, they would certainly not adopt a feature-search mode when a dimension-search mode is equally effective – as is the case when only different-dimension distractors occur. Of note, most studies examining the impact of distractors on visual search have used only different-dimension distractors (e.g., Bacon & Egeth, 1994; Folk, Remington, &

Johnson, 1992; Theeuwes, 1991, 1992). Without the inclusion of a same-dimension distractor, it is not possible to tell whether observers adopted a feature-search or a dimension-search mode, so that the DWA provides a valid explanation for the results of these prior studies as well.

Is interference across all response-time quantiles convincing evidence for involuntary capture?

The quantile analyses indicated that both distractor types interfered even on the fastest trials and this was the case even though interference effects tend to be underestimated in low quantiles (Leber et al., 2013). If there had been trials without distractor interference, these should make up the 20%, 10%, or at least 5% of the fastest trials. Thus, observing significant distractor effects down to at least the 2.5% percentile indicates that both distractor types cause interference on every single trial and that the strength of this interference, rather than the probability of interference, differed between the two distractor types. This would be in line with the assumption that distractors inevitably capture attention, because the first sweep of attentional processing is impenetrable to (voluntary) top-down control (Theeuwes, 1991, 1992, 2010).

However, as responses are given only at the end of a trial, these behavioural results do not reveal the temporal/cognitive locus of the interference effects. Distractors might interfere because they capture attention (Hickey, McDonald, & Theeuwes, 2006; Theeuwes, 1991, 1992, 2010), delay the first attention allocation (to the target, e.g., by competing but not winning the competition for attention; see Moran et al, 2013), clutch attention more firmly (Gaspelin, Ruthruff, & Lien, 2016; Fukuda & Vogel, 2011), or delay the decision process, for instance, due to the increased ambiguity (Meeter & Olivers, 2006; Olivers & Meeter, 2006). The correct answer is likely the most complex version, namely that all of these and perhaps even other processes are influenced by distractor presence; understanding their respective involvement will require the use of electrophysiological markers of the various processes (e.g., Hickey et al., 2006, 2009; Jannati et al., 2013; Liesefeld et al., 2017; Töllner et al., 2012) as well as computational modelling of their complex interactions (e.g., Hulleman & Olivers, 2017; Liesefeld et al., 2016; Narbutas, Kristan, & Heinke, 2017; Moran Liesefeld, Usher, & Müller, 2017; Moran, Zehetleitner, Liesefeld, Müller, & Usher, 2016; Moran et al., 2013; Schwarz & Miller, 2016). It appears likely that more processes are impacted by same-dimension distractors than by different-dimension distractors and that such qualitative as well as quantitative differences explain the differential interference.

Even though being unspecific regarding the cognitive locus of interference effects, our results provide strong evidence that dimension weighting can drastically attenuate distractor interference. In fact, given the relatively huge interference effects for same-dimension distractors (> 4 times the interference caused by different-dimension distractors in the present study and > 10 times the interference caused by different-dimension distractors in most previous studies; between 5 and 25 ms; e.g., Gaspar & McDonald, 2014; Jannati et al., 2013; Theeuwes, 1992; Töllner et al., 2012), it is fair to say that the major share of interference is under (dimensionally constrained) top-down control. Thus, even though there remains some residual interference (because observers cannot or are not willing to reduce it further, see above), this interference is negligible in comparison to the massive interference a distractor can cause when it is not down-weighted (because it is defined in the same dimension as the target).

Salient-signal suppression

The salient-signal-suppression hypothesis claims that distractor signals are suppressed before they can capture attention (Gaspelin, Leonard, & Luck, 2015; 2017; Gaspelin & Luck, 2018a,b; Sawaki et al., 2012), and this idea has been contrasted with the DWA (Gaspar & McDonald, 2014). However, salient-signal suppression is not always successful. For example, in the study of Liesefeld et al. (2017), a salient same-dimension distractor reliably captured attention. In fact, attentional capture likely occurred on every single trial – evidenced by the fact that the amplitude of the distractor N2pc (indicating attentional capture) was the same on fast- and slow-response trials, whereas a difference in N2pc amplitude should emerge if there were some non-capture trials. This is because non-capture trials would *not* elicit a distractor N2pc and produce *fast* responses, and would thus lower the distractor-N2pc amplitude in the fast-response *average* (see Liesefeld et al., 2017, p. 172, for a more detailed explanation).

It is unclear how the salient-signal-suppression hypothesis alone would account for the strong attentional capture by a same-dimension distractor in the Liesefeld et al. study. A combination of dimension-weighting and salient-signal suppression would, however, be in line with available data: when a different-dimension distractor is sufficiently down-weighted by dimension-weighting mechanisms taking effect before the onset of the display (dimension-search mode), salient-signal suppression is strong enough to suppress the residual activation when the display comes up. In contrast, when the distractor signal cannot be sufficiently attenuated in advance, because the distractor is defined in the same dimension as the target, salient-signal suppression is too weak to circumvent attentional capture by the distractor.

Relational coding and linear separability

The present findings are also perfectly in line with the assumption that observers searched for the object that is brighter than the non-targets or tilted more strongly to the right than the non-targets (*relational coding*, Becker, 2010; Becker, Folk, & Remington, 2010, 2013). However, at least for the orientation dimension, it is known that a same-dimension distractor causes massive interference (via attentional capture) even when it is consistently tilted in the opposite direction to the target, thus allowing for differential relational coding of target and distractor (Liesefeld et al., 2017). Similarly, the distractor in Liesefeld et al. (2017) was *linearly separable* from the target (see Bauer, Jolicoeur, & Cowan, 1996a,b; Daoutis, Pilling, & Davies, 2006; Kong, Alais, & van der Burg, 2016), as non-targets had an intermediate value (e.g., -45° distractor, 0° non-targets, and +12° target). In general, it is somewhat difficult to discriminate between predictions from the relational-coding and linear-separability accounts from that of the DWA, because it is unclear what the dimensional structure of saliency-computation mechanisms is.

Colour distractors and feature weighting

One dimension that is particularly difficult as regards its dimensional structure is colour. Although distractors in additional-singleton tasks are most often defined by colour (sometimes paired with colour targets, Gaspelin & McDonald, 2014; Lien, Ruthruff, & Johnston, 2010), we deliberately decided against using colour distractors, because it is not clear whether colour can be conceived of as a single dimension and which colours would belong to the same dimension in terms of saliency computations (see Liesefeld et al., in press; Müller et al., 2003). Already at early stages of colour processing, retinal ganglion cells represent colour in a three-dimensional space (De Valois, Abramov, & Jacobs, 1966; Derrington, Krauskopf, & Lennie, 1984). The psychologically meaningful CIE *Lab* colour space has a similar structure: each colour in this space is defined along the dimensions luminance (*L*), red-green (*a*) and blue-yellow (*b*). It is as yet unknown how this multi-dimensional space is structured for saliency computations and, in fact, it has likely even more than three dimensions (see D'Zmura, 1991; Lindsey et al., 2010). Similar complications may apply to shape as a dimension. It is quite possible (and at least for colour well established) that observers can selectively process specific sub-dimensions, so that results may appear to support attentional sets for specific features. Because of this inherent interpretational difficulty, it would appear to be a good strategy to first restrict evaluations of the DWA to dimensions that are 'well-behaved' in that their (sub-)dimensional structure is relatively clear (such as orientation, luminance, motion speed/direction, size, etc.). Nevertheless, the same general principles of dimension weighting that are observed for other dimensions should also apply to the various colour sub-dimensions. Thus, once the dimensional structure of saliency computations for colour is uncovered, it should be possible to verify predictions made by the DWA using colour stimuli as well (for more details on the special status of colour, see Liesefeld et al. in press; Liesefeld & Müller, under revision).

Similarity

Distractors defined in the same dimension as the target are necessarily more similar to the target than distractors defined in a different dimension. In fact, distractors defined in a different dimension are, in a way, maximally dissimilar from the target. Thus, the small interference by different-dimension distractors can also be explained by their dissimilarity to the target (see Duncan & Humphreys, 1989; Liesefeld et al., 2016; van Zoest & Donk, 2004). However, in this interpretation, it is surprising that observers were apparently unable to ignore a 45° distractor when searching for a 12° target and to ignore a 98% intensity distractor when searching for a 59% intensity target – feature differences that are so huge that the contrast is sufficient to produce pop-out (i.e., to efficiently guide attention; see Liesefeld et al., 2016; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992)[1]. To maintain a feature-weighting or target-template

[1]This was confirmed by a control experiment in which 12 observers searched for either a 45°-tilted target among 12°-tilted non-targets or for a 98%-intensity target among 59%-intensity non-targets That is, roles were changed in that

explanation of these results, one would have to assume a very coarse feature-specific filter or a very imprecise template to explain why these distractors could not be ignored more effectively. In fact, the filter would likely have to be so coarse that it would usually comprise the whole dimension, so that the respective model would make virtually identical predictions as the DWA.

In sum, although the present results do certainly not settle the debate and do not exclude all alternative interpretations, we believe that they provide a crucial piece of evidence for the DWA: observers in our task strongly down-modulated a distracting signal when they were searching for a target defined in a different dimension, and did/could not or only weakly down-modulate the physically identical signal when they were searching for a target defined in the same dimension, even though it caused massive interference. We consider this strong indication that observers are unable to limit their search to a particular feature, but the best they can do is to boost any signal from the target dimension and/or attenuate any signal from the distractor dimension. In brief: (voluntary) top-down control in visual search is dimensionally constrained.

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the previous distractors became targets and the previous targets became non-targets. Target condition (orientation vs. luminance) was blocked and the order of blocks was balanced across participants. The goal was to determine whether the contrast between these two objects was sufficient to produce efficient search (i.e., flat slopes of the function relating response times to the number of non-targets). Set-size was manipulated between 7 and 19 according to the design developed by Liesefeld et al. (2016, Experiments 2 and 3), which was adapted to the present study in that participants had to indicate the position of the notch (classification task) instead of deciding whether a target was present or absent. Results proved that both searches were highly efficient (-1 ms/item for orientation searches and 3 ms/item for luminance searches), indicating that the respective objects are sufficiently dissimilar to produce reliable pop-out (see Liesefeld et al., 2016, for details on the theoretical background).

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