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Distractor handling via dimension weighting

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Abstract

Salient-but-irrelevant objects have the potential to distract attention. Objects are salient if they differ from their surround in some feature dimension, such as shape, orientation, or motion. One way to reduce distraction therefore is to attenuate all saliency signals from the respective feature dimension. This mechanism, or strategy, which follows from a broader theory of attentional selection termed Dimension-Weighting Account (DWA), is very powerful, as evidenced by the massive distractor interference observed when it is ineligible. However, it also consumes scarce cognitive resources, so that it is not always employed and often complemented by other mechanisms of distractor handling. These alternative mechanisms might be less effective and/or have negative side effects.

Keywords: dimension-weighting account; distractor suppression; visual search; attentional capture; priority map; search strategies

Salient objects standing out from a visual scene tend to summon attention. This is beneficial if these objects are relevant to the task at hand (*targets*), but harmful if they are irrelevant (*distractors*). Even a single misallocation of attention towards a distractor (*attentional capture*) can become costly in terms of time required to complete a laboratory task (up to at least 220 ms [1**]) and can have serious consequences in real-life scenarios (e.g., causing a car accident). Fortunately, salient but irrelevant distractors can be quite effectively ignored in many situations, producing only mild impairments. This is due to appropriate cognitive control mechanisms being in place that help reduce, or entirely avoid, distraction. One putative control mechanism follows from the dimension-weighting account (DWA) [2,3]: The core assumption of the DWA is that the human visual system dynamically up- and/or down-weights saliency signals from the various feature dimensions in line with task goals as well as task history (Box 1). Accordingly, the down-weighting of saliency signals from the distractor dimension is one readily available means to avoid distraction by a salient stimulus. In the present article, we outline a theory of dimension-weighting-based distractor handling by reviewing and reinterpreting the existing evidence from ours and other research groups and highlighting situations under which observers cannot or can partially or completely down-weight the distractor dimension to reduce distractor interference.

Box 1: The Dimension-Weighting Account

The general saliency-computation architecture behind the DWA is sketched in Figure 1. As in Guided Search [4,5*], attention allocation is assumed to be guided by a spatial representation of the visual scene, often referred to as *priority map*. Locations with a high value on the priority map tend to summon attention. The priority map integrates input from various saliency maps, each coding for local feature contrasts in the respective feature dimension. That is, each location on a dimension-specific saliency map codes for the difference in the respective feature space between the object at that location and the surrounding objects; it represents these differences, rather than the actual feature values. The priority map, in turn, contains only information on the integrated difference values and is therefore void of information on features *and* dimensions. The crucial and eponymous assumption of the DWA is that the degree of information transfer (the weights on the connections) from the individual, dimension-specific saliency maps to the overall priority map can change dependent on experience (history) and behavioral goals (voluntary control). This assumption is supported by a plethora of neuropsychological and behavioral evidence from a broad range of search paradigms and experimental effects (see [6**] for a recent, comprehensive review).

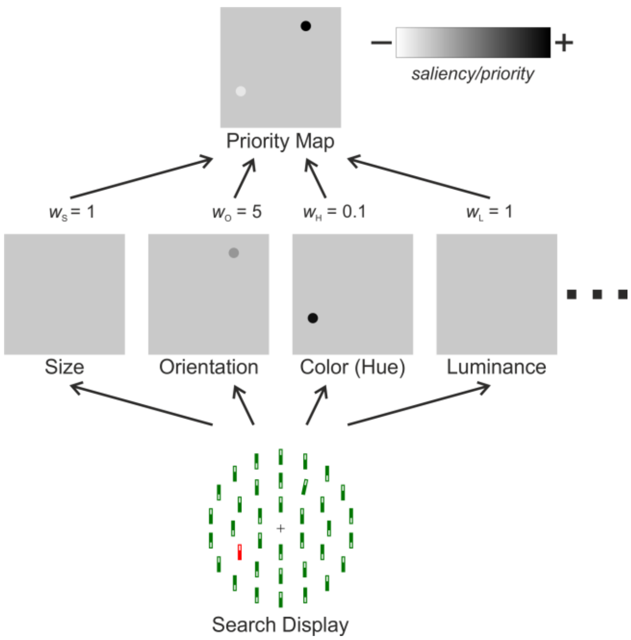

Figure 1. Simplified sketch of one possible implementation of dimension-based distractor suppression. The orientation singleton is of moderate saliency, but of maximum priority due to the amplification (weight > 1) on the connection between orientation saliency map and priority map. The more salient, red distractor object, in contrast, receives a lower value (is suppressed) on the priority map due to the attenuation (weight < 1) during the signal transfer/integration from the color saliency map to the priority map; potentially, the final priority value associated with the red object is even lower than that of the background. Saliency is determined by local feature contrast [7*]. Weights are thought to be influenced by task goals (Which dimension was instructed as relevant/irrelevant?) and task history (Which dimension was processed/suppressed on previous trials?).

Failure of dimension-based control

To appreciate a thing, it is often best to study a situation in which it is unavailable. As an example, people do not usually appreciate the presence of oxygen until it gets scarce (e.g., after a night’s sleep in a closed car) and will likely continue to waste natural resources (clean water, oil, etc.) until they deplete. Liesefeld and colleagues [1**] recently measured electroencephalographic correlates of attentional dynamics in a situation in which cognitive control was greatly needed, but dimension weighting was of no help: Observers had to search for a 12°-tilted target bar among vertical non-target bars , with an additional salient object (*distractor*) being present on two thirds of all trials (*additional-singleton task*). Crucially, in this study, the distractor bar stood out in the same dimension as the target, namely orientation (tilted 45° into the opposite direction; see Fig. 2a; see [8, 9] for comparable behavioral studies). With such a *same-dimension distractor*, down-weighting saliency signals from the distractor dimension (orientation) would inevitably also down-weight the target signal, so that dimension weighting was ineligible for distractor handling. Accordingly, the observed pattern of N2pc components (an electrophysiological correlate of attention allocation [10*,11]) indicated that the more salient 45° distractor reliably captured attention, that is: attention first involuntarily moved towards the salient distractor, before it was re-allocated to the target. The misallocation (capture) of attention caused a delay of target processing, as compared to a no-distractor baseline (Fig. 3). In fact, distractor presence delayed responses by more than 200 ms (indicative of near-invariable capture)! Thus, when dimension weighting is unavailable as a strategy to handle distraction, distractor interference is massive – highlighting the crucial role that dimension weighting, when available, can play to reduce distractor interference.

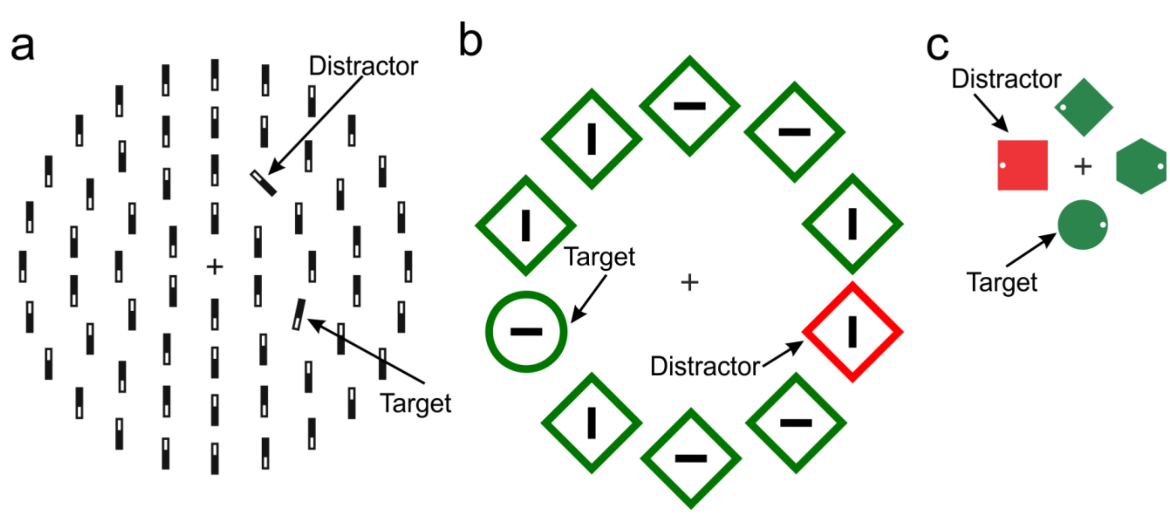

Figure 2. Sketches of various displays used to examine distractor handling in visual search. (a) Particularly dense array, featuring many non-targets (*here:* vertical bars), to gain maximum control over local feature contrast (i.e., stimulus saliency); both target (*here:* 12°-tilted bar) and same-dimension distractor (*here:* 45°-tilted bar) stand out from their surround (see *Failure of dimension-based control*). (b) Most studies use a moderate number of non-targets (*here:* green diamonds); target and different-dimension distractor (*here:* green circle and red distractor) stand out from their surround (see *Successful dimension-based control*). (c) A display with only few and heterogeneous non-targets (*here:* green diamond and green hexagon); whereas the different-dimension distractor (*here:* red square) stands out due to its relatively high local feature contrast, the target (*here:* green circle) does not (see *Other mechanisms of distractor handling*).

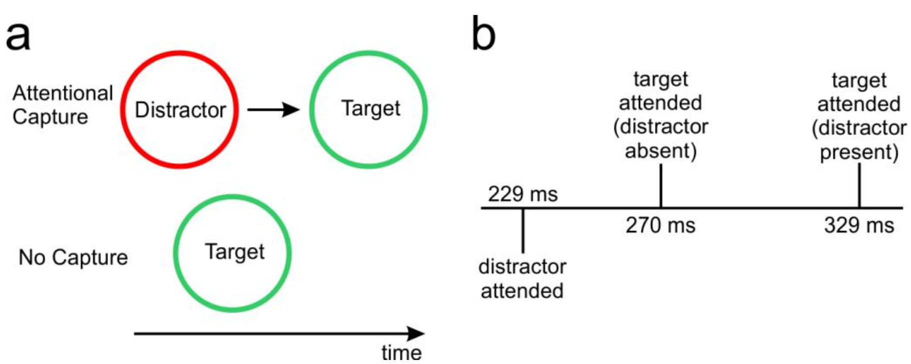

Figure 3. Schematic illustration of the theoretical time-course of attention allocations when attention is captured. (a) In terms of serial-search models [4,5], attentional capture means that the distractor is first attended and, following this misallocation, attention is re-allocated towards the target. This also implies that the target is attended earlier when the distractor did not capture attention (because it was not present in the display or capture was successfully avoided). Furthermore, as the distractor captures attention because it is more salient than the target, attention allocation towards the distractor should be faster than even to the target on no-capture (distractor-absent) trials (the more salient an object is, the faster it can be attended [11]). (b) Exactly this pattern was observed in Liesefeld et al. [1**].

Dimension weighting is, of course, also ineligible for distractor handling when the distractor has the same feature as the target (e.g., both have the same shade of red), such as in many studies using the spatial-cueing paradigm pioneered by Folk and colleagues [12]. Thus, most findings of *contingent capture* (i.e., an uninformative pre-cue captures attention if it has the same feature – and therefore also stands out in the same dimension – as the subsequently presented target) are broadly in line with the DWA (see also section on *Color* below). In fact, there is evidence from this line of research that attentional sets can comprise the whole target dimension [13-15] or (negatively) the whole distractor dimension [16**,17*]. Perhaps the most compelling evidence for such dimension-encompassing attentional sets stems from single-cell recordings in monkeys [18**]: when the monkey looked for motion (vs. color) changes, neurons in area MT showed a sustained increase in firing rate prior to motion onset and an up-modulation during motion processing [see also 19]. Importantly, responses to motion were increased even in neurons that were *not* well tuned to the observed motion direction and speed. This effect pattern is indicative of a persistent neuronal boost of signals from the whole target *dimension* (instead of specific target *features*; see [20,21] for converging human fMRI evidence for the DWA).

Successful dimension-based control

In his classical studies, Theeuwes [22,23] showed that search for a shape target is hampered by a color distractor. This finding challenges the DWA, because with such a *different-dimension distractor*, dimension weighting should be effective. However, more recent, electrophysiological evidence suggests that a different-dimension distractor does not typically capture attention, but is indeed successfully suppressed before it can do so. Jannati, Gaspar, & McDonald [24] for example, showed that a color distractor during search for a shape target (as displayed in Fig. 2b) does not elicit an N2pc, but a P_D indicating suppression of the distractor instead of attentional capture [25, but see 26*]. Furthermore, attention allocation to the target (target N2pc) is not delayed with different-dimension distractors.This stands in sharp contrast to the same-dimension distractor findings of Liesefeld and colleagues [1**], where the distractor elicited first an N2pc and only afterwards a P_D (i.e., was first attended and only afterwards suppressed) and the target N2pc was delayed by distractor presence.

Liesefeld, Liesefeld, and Müller [27**] directly pitted situations against each other in which selective dimension weighting was or was not possible: One group of observers searched for an object that was brighter than the dim non-targets (luminance target) and another group searched for an object that was tilted more strongly than the vertical non-targets (orientation target). On two thirds of trials, an additional, irrelevant object was present that was (unpredictably) either brighter than the luminance target (luminance distractor) or tilted more strongly than the orientation target (orientation distractor). Crucially, the two groups of observers received different targets, but the same distractors, so that the physically identical distractor served either as a same-dimension or a different-dimension distractor, thus excluding any differences in stimulus features (and therefore saliency) between same- and different-dimension distractors. In a control study, we showed that the same-dimension distractors were so dissimilar to the targets that the respective contrast (searching for the previous distractors among a homogeneous background of previous targets) produced reliable pop-out (i.e., very efficient search in which the target is found almost immediately). Yet, these very dissimilar, same-dimension distractors caused massive response-time costs of more than 250 ms, whereas different-dimension distractors delayed response times by only around 50 ms. In terms of the architecture sketched in Figure 1, this indicates that different-dimension distractors were heavily down-weighted, while same-dimension distractors were not down-weighted (or even up-weighted). Thus, dimension weighting is indeed effective with different-dimension distractors, substantially reducing their interference as compared to that caused by same-dimension distractors (see [27**] for detailed rebuttals of various alternative explanations).

Partial dimension-based control

In certain situations, a different-dimension distractor does capture attention; e.g., when the target varies across trials, the distractor elicits an N2pc [28-30]. However, the target N2pc emerges at the same time as the distractor N2pc and is not delayed by distractor presence. This is indicative of a mixture of trials with and without attentional capture: the distractor N2pc stems from trials in which capture occurred, but these are so few that they do not actually delay the target N2pc in the grand average, which is, instead, dominated by the preponderance of trials on which capture was successfully avoided. An across-study comparison of behavioral interference effects supports this interpretation: interference by different-dimension distractors is around 100 ms or smaller during search for variable targets or variable distractors [28,31*], which is considerably less than the 200 ms or 250 ms observed by Liesefeld et al. for (constant) *same*-dimension distractors during search for constant targets [1**,27**]. During search for constant targets, the interference by *different*-dimension distractors is typically no larger than 25 ms (e.g. [23,24]). If the Liesefeld et al. [1**,27**] same-dimension results are taken as a baseline (i.e., maximal distractor interference in the absence of dimension weighting), all previous studies examining different-dimension distractors actually demonstrate a profound reduction of distractor interference via dimension weighting. This reduction is somewhat modulated by target and distractor predictability: distractor handling via dimension weighting is improved in predictable contexts.

Probably, dimension weighting, though in principle eligible, is not always (fully) applied for handling different-dimension distractors: it is sometimes reduced due to lapses of cognitive control [32**], because cognitive resources are demanded by other aspects of the task (handling varying targets/distractors or general task difficulty [28,31,33]), or simply because (some) observers are at times somewhat ‘lazy’ [34,35]. That down-weighting of distractor dimensions costs some effort is also supported by findings indicating that it requires incentives and time to develop [36-38]. Variation in the intensity of dimension-based control would also explain why variation in fMRI-measured frontal brain activity predicts distractor interference [39,40]: when people make an effort in down-weighting the distractor dimension, frontal, control-related brain regions [41] are active and distraction is reduced, though possibly not fully eliminated.

Other mechanisms of distractor handling

The accumulated evidence indicates that dimension weighting is a powerful mechanism for distractor handling, but it is certainly not the only mechanism serving this crucial function. Indeed, various mechanism, or strategies, might be in place that complement dimension weighting, potentially at different stages of processing and/or under different search conditions [13,42,43].

Spatial suppression. Sauter, Liesefeld, Zehetleitner, and Müller [44**] used a target/distractor combination similar to that of Liesefeld et al. [1**] (i.e., a same-dimension distractor), so that dimension-weighting was ineligible for distractor handling. However, the distractor appeared in one region with a 90% probability, thus providing space-based suppression as an alternative mechanism for distractor handling. Having no other choice, participants made plentiful use of this alternative mechanism (as compared to a control group with a different-dimension distractor, for which the more efficient dimension-weighting strategy was eligible). The downside of this space-based suppression was that in the same-dimension distractor group (in contrast to the control group and otherwise comparable studies [45,46]), processing of the target in the frequent distractor area was hampered as well.

Template-based suppression. As evident from Fig. 1, dimension weighting only applies when search is guided by the priority map. Under certain conditions, it might be advisable to bypass the priority map and use other strategies to find the target. Gaspelin and colleagues

[32**,47**], for instance, used a search paradigm in which each non-target had a different feature (typically different shapes; Fig. 2b). Such heterogeneous non-targets are well known to induce inefficient search [48], probably because the target does not produce a unique peak on the priority map. Furthermore, observers treat sparse search displays (with only few objects, such as in the Gaspelin et al. studies) differently to dense search displays [49*]. Under such conditions, observers potentially switch from a strategy based on priority-map guidance to successive template matching (i.e., serial search [43,50]; for other ideas on search dichotomies, see [50-53]). Of importance here, in such an inefficient-search paradigm, Gaspelin and Luck [47**] observed evidence for template-based instead of dimension-based suppression (what they call 'first order' vs. 'second order' suppression). Similarly, evidence for so-called negative search templates (representations of the distractor feature) is typically obtained in tasks that are suited to induce inefficient search [e.g., 54*].

Observations of strong attentional capture by same-dimension orientation and luminance distractors indicate that such negative templates were not employed in the studies of Liesefeld et al. [1**,27**]. Potentially, bypassing the priority map and using negative templates may not have been an efficient strategy in their paradigm because of the dense display arrangement (see Fig. 2 for a comparison of display arrangements). Alternatively, negative templates (i.e., 'first-order' suppression) may only be available in certain dimensions, most probably color.

Color. There is indeed some indication that searching for color targets is different to searching for targets standing out in other dimensions, such as orientation, size, luminance, or shape (which all can guide search as well [5*]). For example, searching for a color target is less impaired by simultaneously looking for another target standing out in a different dimension, compared to searching for an orientation or shape target [13**]. Furthermore, in contrast to the same-dimension orientation and luminance distractors in Liesefeld et al. [1**,27**], a color distractor is efficiently suppressed during search for a color target [55]. Specialized mechanisms that ease searching for or avoiding of specific colors might have evolved due to the exceptional behavioral importance of this feature dimension (e.g., searching for ripe fruits). Alternatively, color may be better considered as consisting of multiple dimensions, in line with the multidimensional structure of retinal color receptors, neuronal color pathways, and color spaces (but see [56*]; see [6**] for a more comprehensive discussion on the special status of color).

Conclusion

The reviewed evidence indicates that dimension weighting provides a powerful mechanism of distractor handling. Whether target and distractor are defined in the same (vs. different) dimension(s) determines whether dimension weighting *can* be applied as a strategy of distractor handling, in principle. But there are various other influences that determine whether and how consistently this form of distractor handling *is* applied, in actuality. When search is guided by the priority map, same-dimension distractors (virtually) always capture attention, because this capture cannot be avoided; by contrast, different-dimension distractors capture attention only if voluntary control is diverted or (subjectively) not worthwhile. The ability or willingness to employ this form of top-down control might be a crucial personality trait [35**,57**].

Acknowledgments

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References

Papers of special interest (*) or outstanding interest (**)

1. **Liesefeld HR, Liesefeld AM, Töllner T, Müller HJ: **Attentional capture in visual search: Capture and post-capture dynamics revealed by EEG.** Neuroimage 2017, **156**:166-173. doi:10.1016/j.neuroimage.2017.05.016
The first observation of (covert) attentional dynamics when distractor handling initially fails completely and recovers only later: Electrophysiological markers indicate that attention is first allocated towards a same-dimension distractor and only then to the target. This caused a delay in target processing, and the distractor was actively suppressed after it had captured attention.
2. Found A, Müller HJ: **Searching for unknown feature targets on more than one dimension: Investigating a 'dimension-weighting' account.** Percept Psychophys 1996, **58**:88-101. doi:10.3758/BF03205479
3. Müller HJ, Heller D, Ziegler J: **Visual search for singleton feature targets within and across feature dimensions.** Percept Psychophys 1995, **57**:1-17. doi:10.3758/BF03211845
4. Wolfe JM: **Guided search 4.0: Current progress with a model of visual search.** In *Integrated models of cognitive systems.* Edited by Gray W. Oxford University Press; 2007:99–119.
5. *Wolfe JM, Horowitz TS: **Five factors that guide attention in visual search.** Nat Hum Behav 2017, **1**:58. doi:10.1038/s41562-017-0058
A concise summary of guided search and the various factors that influence search, including an overview of the available evidence regarding which target attributes provide guidance (are found efficiently).

6. **Liesefeld HR, Liesefeld AM, Pollmann S, Müller HJ: **Biasing allocations of attention via selective weighting of saliency signals: behavioral and neuroimaging evidence for the Dimension-Weighting Account.** In *Current Topics in Behavioral Neurosciences: Processes of Visuo-spatial Attention and Working Memory*. Edited by Hodgson T. Springer; in press

A comprehensive review of behavioral and neuroimaging evidence for the dimension-weighting account (DWA). Changes in dimensional weights are observed as a function of task history (in particular, the target dimension on the previous trial) and search goals (information on the target-defining dimension). This chapter also contains sections on distractor handling, on the special status of color, and on the relation between DWA and related theories.

7. *Liesefeld HR, Moran R, Usher M, Müller HJ, Zehetleitner M: **Search efficiency as a function of target saliency: The transition from inefficient to efficient search and beyond.** J Exp Psychol Hum Percept Perform 2016, **42**:821-836. doi:10.1037/xhp0000156

Featuring dense display arrangements, this study shows that search efficiency is a continuous function of feature contrast between the target and surrounding non-targets. The article also contains extensive discussion of why display density is important for controlling saliency.

8. Kumada T: **Limitations in attending to a feature value for overriding stimulus-driven interference.** Percept Psychophys 1999, **61**:61-79. doi:10.3758/BF03211949

9. van Zoest W, Donk M: **Bottom-up and top-down control in visual search.** Percept 2004, **33**:927-937. doi:10.1068/p5158

10. *Luck SJ: **Electrophysiological correlates of the focusing of attention within complex visual scenes: N2pc and related ERP components.** In *The Oxford handbook of event-related potential components.* Edited by Kappenman ES, Luck SJ. Oxford University Press; 2012:329-360. doi:10.1093/oxfordhb/9780195374148.001.0001

A useful review on the N2pc as an indicator of attentional dynamics. Evidence from the N2pc component turned out to be crucial in the debate on distractor handling in visual search [e.g., 23].

11. Töllner T, Zehetleitner M, Gramann K, Müller HJ: **Stimulus saliency modulates pre-attentive processing speed in human visual cortex.** PLoS ONE 2011, **6**:e16276. doi:10.1371/journal.pone.0016276

12. Folk CL, Remington RW, Johnston JC: **Involuntary covert orienting is contingent on attentional control settings.** J Exp Psychol Hum Percept Perform 1992, **18**:1030-1044. doi:10.1037/0096-1523.18.4.1030

13. **Biderman D, Biderman D, Zivony A, Lamy D: **Contingent capture is weakened in search for multiple features from different dimensions.** J Exp Psychol Hum Percept Perform 2017, **43**:1974-1992. doi:10.1037/xhp0000422

Shows that simultaneously searching for targets in two dimensions incurs a cost compared to searching for targets in only one dimension, indicating that limited attentional weights are distributed across dimensions. The authors also speculate that search templates might work at a post-selective stage and discuss that, compared to other dimensions such as orientation and shape, preparing for color targets is less impaired by simultaneously preparing for additional targets – thus providing another indication of a special status of color in visual search.

14. Harris AM, Becker SI, Remington RW: **Capture by colour: Evidence for dimension-specific singleton capture.** Atten Percept Psychophys 2015, **77**:2305-2321. doi:10.3758/s13414-015-0927-0

15. Folk CL, Anderson BA**: Target-uncertainty effects in attentional capture: Color-singleton set or multiple attentional control settings?.** Psychon Bull Rev 2010, **17**:421-426. doi:10.3758/PBR.17.3.421

16. *Vatterott DB, Mozer MC, Vecera SP: **Rejecting salient distractors: Generalization from experience.** Atten Percept Psychophys 2018, **80**:485-499. doi:10.3758/s13414-017-1465-8

Shows that observers can reduce distractor interference from the whole color dimension if sufficiently incentivized and trained.

17. *Kadel H, Feldmann-Wüstefeld T, Schubö A: **Selection history alters attentional filter settings persistently and beyond top-down control.** Psychophysiology 2017, **54**:736-754. doi:10.1111/psyp.12830

Observers trained on the behavioral importance of color in an unrelated task show increased capture by color singletons in a subsequent additional-singleton task. This was the case even though a different color was used as a distractor in the search task and even when the upcoming search display was predictable – thus indicating sustained up-weighting of the whole color dimension as a result of task history.

18. **Schledde B, Galashan FO, Przybyla M, Kreiter AK, Wegener D: **Task-specific, dimension-based attentional shaping of motion processing in monkey area MT.** J Neurophysiol 2017, **118**:1542-1555. doi:10.1152/jn.00183.2017

Reports an increase in firing rates of neurons in monkey MT when the task is to monitor for motion-speed changes, but not when the task is to monitor for color changes. Of note, this increase occurs already prior to motion onset and firing rates are increased during motion processing even in neurons that do not or only weakly code for the presented motion. This persistent enhancement of the whole target dimension (motion), rather than just of specific features, might constitute the neuronal mechanism that implements dimension weighting.

19. Chawla D, Rees G, Friston KJ: **The physiological basis of attentional modulation in extrastriate visual areas.** Nat Neurosci 1999, **2**:671-676. doi:10.1038/10230

20. Pollmann S, Weidner R, Müller HJ, von Cramon DY: **A fronto-posterior network involved in visual dimension changes.** J Cogn Neurosci 2000, **12**:480-494. doi:10.1162/089892900562156

21. Pollmann S, Weidner R, Müller HJ, Maertens M, von Cramon DY: **Selective and interactive neural correlates of visual dimension changes and response changes.** Neuroimage 2006, **30**:254-265. doi:10.1016/j.neuroimage.2005.09.013

22. Theeuwes J: **Cross-dimensional perceptual selectivity.** Percept Psychophys 1991, **50**:184-193. doi:10.3758/BF03212219

23. Theeuwes J: **Perceptual selectivity for color and form.** Percept Psychophys 1992, **51**:599-606. doi:10.3758/BF03211656

24. Jannati A, Gaspar JM, McDonald JJ: **Tracking target and distractor processing in fixed-feature visual search: Evidence from human electrophysiology.** J Exp Psychol Hum Percept Perform 2013, **39**:1713-1730. doi:10.1037/a0032251,

25. Hickey C, Di Lollo V, McDonald JJ: **Electrophysiological indices of target and distractor processing in visual search.** J Cogn Neurosci 2009, **21**:760-775. doi:10.1162/jocn.2009.21039

26. *Livingstone AC, Christie GJ, Wright RD, McDonald JJ: **Signal enhancement, not active suppression, follows the contingent capture of visual attention.** J Exp Psychol Hum Percept Perform 2017, **43**:219-224. doi:10.1037/xhp0000339
Casts doubt on the P_D as an electrophysiological marker of distractor suppression. When disentangling onset of the distractor and onset of the target in a spatial-cueing paradigm, the P_D emerges time-locked to target onset, and not to distractor onset.

27. ** Liesefeld HR, Liesefeld AM, Müller HJ: **Distractor-interference reduction is dimensionally constrained.** Vis Cogn under review

Directly compares how much same-dimension vs. different-dimension distractors interfere with search. Importantly, this study uses physically identical distractors in either role, thus ruling out any differences in saliency: a luminance distractor is a same-dimension distractor when searching for a luminance target and a different-dimension distractor when searching for an orientation target, and vice versa for an orientation distractor. Distractor interference on RTs is massive (> 250 ms) for same-dimension and relatively small (~50 ms) for different-dimension distractors.

28. Burra N, Kerzel D: **Attentional capture during visual search is attenuated by target predictability: Evidence from the N2pc, Pd, and topographic segmentation.** Psychophysiology 2013**50**:422-430. doi:10.1111/psyp.12019

29. Hickey C, McDonald JJ, Theeuwes, J: **Electrophysiological evidence of the capture of visual attention.** J Cogn Neurosci 2006, **18**:604-613. doi:10.1162/jocn.2006.18.4.604

30. Kiss M, Grubert A, Petersen A, Eimer M: **Attentional capture by salient distractors during visual search is determined by temporal task demands.** J Cogn Neurosci 2012, **24**:749-759. doi:10.1162/jocn_a_00127

31. Kerzel D, Barras C: **Distractor rejection in visual search breaks down with more than a single distractor feature.** J Exp Psychol Hum Percept Perform 2016, **42**:648-657. doi:10.1037/xhp0000180

32. **Gaspelin, N, Luck SJ: **The role of inhibition in avoiding distraction by salient stimuli.** Trends Cogn Sci 2018, **22**:79-92. doi:10.1016/j.tics.2017.11.001

Recent review on distractor handling from the perspective of the authors, which stands somewhat in contrast to our perspective, probably owing to a focus on different types of search tasks (i.e., few and heterogenous non-targets vs. many and homogenous non-targets in our work).

33. *Barras C, Kerzel D: **Salient-but-irrelevant stimuli cause attentional capture in difficult, but attentional suppression in easy visual search.** Psychophysiology 2017, **54**:1826-1838. doi:10.1111/psyp.12962

Show that different-dimension distractors capture attention when the search task is difficult, but not when it is easy. This may indicate that dimension weighting is less rigorously employed when cognitive resources are consumed by other aspects of the task.

34. Egeth HE, Leonard CJ, Leber AB: **Why salience is not enough: Reflections on top-down selection in vision.** Acta Psychol (Amst) 2010, **135**:130-132. doi:10.1016/j.actpsy.2010.05.012

35. **Irons JL, Leber AB: **Characterizing individual variation in the strategic use of attentional control.** J Exp Psychol Hum Percept Perform 2018, advance online publication. doi:10.1037/xhp0000560

Demonstrate and discuss in detail interindividual variation in the adoption of efficient search strategies. Choice of strategy seems to depend on how effortful the strategy is perceived by the individual observer and how willing the observer is to invest mental effort (i.e., ‘laziness’). Such variation in strategy use makes it difficult to unambiguously interpret sporadic attentional capture by different-dimension distractors as evidence against the in-principle availability of a dimension-based strategy of distractor handling.

36. Geyer T, Müller HJ, Krummenacher J: **Expectancies modulate attentional capture by salient color singletons.** Vision Res 2008, **48**:1315-1326. doi:10.1016/j.visres.2008.02.006

37. Müller HJ, Geyer T, Zehetleitner M, Krummenacher J:**Attentional capture by salient color singleton distractors is modulated by top-down dimensional set.** J Exp Psychol Hum Percept Perform 2009, **35**:1-16. doi:10.1037/0096-1523.35.1.1

38. *Zehetleitner M, Goschy H, Müller HJ: **Top-down control of attention: It's gradual, practice-dependent, and hierarchically organized.** J Exp Psychol Hum Percept Perform 2012, **38**:941-957. doi:10.1037/a0027629

Following up on [31], this study demonstrates that incentives and practice are necessary to handle a given distractor and that training to handle a given distractor does not transfer to distractors standing out in a non-trained dimension.

39. de Fockert J, Rees G, Frith C, Lavie N: **Neural correlates of attentional capture in visual search.** J Cogn Neurosci 2004, **16**:751-759. doi:10.1162/089892904970762

40. Leber AB: **Neural predictors of within-subject fluctuations in attentional control.** J Neurosci 2010, **30**:11458-11465. doi:10.1523/JNEUROSCI.0809-10.2010

41. Corbetta M, Shulman GL: **Control of goal-directed and stimulus-driven attention in the brain.** Nat Rev Neurosci 2002, **3**:201-215. doi:10.1038/nrn755

42. Rangelov D, Müller HJ, Zehetleitner M: **Dimension-specific intertrial priming effects are task-specific: Evidence for multiple weighting systems.** J Exp Psychol Hum Percept Perform 2011, **37**:100-114. doi:10.1037/a0020364

43. Chan LH, Hayward WG: **Feature integration theory revisited: Dissociating feature detection and attentional guidance in visual search.** J Exp Psychol: Hum Percept Perform 2009, **35**:119-132. doi:10.1037/0096-1523.35.1.119

44. **Sauter M, Liesefeld HR, Zehetleitner M, Müller HJ: **Region-based shielding of visual search from salient distractors: Target detection is impaired with same- but not different-dimension distractors.** Atten Percept Psychophys 2018, **80**:622-642. doi:10.3758/s13414-017-1477-4

Showed that when dimension-weighting is ineligible as a strategy to handle distraction, observers make more extensive use of an alternative, space-based strategy, even though it has negative side effects (hampering target processing in addition to reducing distractor interference).

45. Ferrante O, Patacca A, Di Caro V, Della Libera C, Santandrea E, Chelazzi L : **Altering spatial priority maps via statistical learning of target selection and distractor filtering.** Cortex 2018, **10**:267-95. doi:10.1016/j.cortex.2017.09.027

46. Goschy H, Bakos S, Müller HJ, Zehetleitner M: **Probability cueing of distractor locations: Both intertrial facilitation and statistical learning mediate interference reduction.** Front Psychol 2014, **5**:1195. doi:10.3389/fpsyg.2014.01195

47. **Gaspelin N, Luck SJ: **Distinguishing among potential mechanisms of singleton suppression.** J Exp Psychol Hum Percept Perform 2018, **44**:626-644. doi:10.1037/xhp0000484

Tested various theories of distractor handling against each other and observed evidence for a 'first-order' (i.e., template-based) suppression of color distractors in search displays with few and heterogenous non-targets. It remains to be tested which type of suppression is employed with other search displays and with other distractor dimensions.

48. Duncan J, Humphreys GW: **Visual search and stimulus similarity.** Psychol Rev 1989, **96**:433-458. doi:10.1037/0033-295X.96.3.433

49. *Rangelov D, Müller HJ, Zehetleitner M: **Failure to pop out: Feature singletons do not capture attention under low signal-to-noise ratio conditions.** J Exp Psychol Gen 2017, **146**:651-671. doi:10.1037/xge0000284

Showed that qualitatively different processes occur in search tasks with sparse (few non-targets) compared to dense (many non-targets) search displays. One reason is that in sparse displays, targets do not pop out consistently, i.e., they do not achieve high salience and are therefore not found efficiently.

50. Treisman AM, Gelade, G: **A feature-integration theory of attention.** Cogn Psyhol 1980, **12**:97-136. doi:10.1016/0010-0285(80)90005-5

51. Treisman A, Gormican S: **Feature analysis in early vision: Evidence from search asymmetries.** *Psychol Rev* 1988, **95**:15-48. doi:10.1037/0033-295X.95.1.15

52. Bacon WF, Egeth HE: **Overriding stimulus-driven attentional capture.** Percept Psychophys 1994, **55**:485-496. doi:10.3758/BF03205306

53. Leber AB, Egeth HE: **It's under control: Top-down search strategies can override attentional capture.** *Psychon Bull Rev* 2006, **13**:132-138. doi:10.3758/BF03193824

54. *Reeder RR, Olivers CNL, Pollmann S: **Cortical evidence for negative search templates.** Vis Cogn 2017, **25**:278-290. doi:10.1080/13506285.2017.1339755

Report behavioral and neuroimaging evidence for the use of negative search templates, i.e., working-memory representations that allow for efficient distractor handling. Such negative templates might complement dimension-based distractor handling in certain situations.

55. Gaspar JM, McDonald JJ: **Suppression of salient objects prevents distraction in visual search.** J Neurosci 2014, **34**:5658-5666. doi:10.1523/JNEUROSCI.4161-13.2014

56. *Martinovic J, Wuerger SM, Hillyard SA, Müller MM, Andersen SK**: Neural mechanisms of divided feature-selective attention to color.** Neuroimage 2018, **181**:670-682. doi:10.1016/j.neuroimage.2018.07.033

Used steady-state visually evoked potentials (SSVEPs) and four overlaying sets of random-dot kinematograms of different colors (two relevant, two irrelevant) to examine how well attention can 'tune in' to a specific combination of colors. Results show that selectivity depends on the distance in color space along a single continuum, indicating that in this type of attention task, color is treated as one dimension.

57. **Gaspar JM, Christie GJ, Prime DJ, Jolicoeur P, McDonald JJ: **Inability to suppress salient distractors predicts low visual working memory capacity.** Proc Natl Acad Sci U S A 2016, **113**:3693-3698. doi:10.1073/pnas.1523471113

Observed variation in distractor handling that is predictive of visual-working memory capacity. This indicates that the ability to use effective distractor-handling strategies is a crucial cognitive function that has implications for a broader range of tasks and, potentially, for cognitive performance in general.