Top-down shielding from distraction in visual attention: Factors of influence

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Harriet-Rosita Goschy

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Graduate School of
Systemic Neurosciences
LMU Munich

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Harriet-Rosita Goschy

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PD Dr. Michael Zehetleitner *(1st Supervisor)*

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Summary

The present work examines top-down shielding from distraction in visual attention; that is, under which circumstances can the intentions and goals of an observer counteract the bottom-up salience of irrelevant distractors. Several factors of influence will be considered: First, prior experience with distractors, i.e. did observers previously acquire an effective distractor shielding strategy; second, intra- vs. cross-dimensionality of distractors, i.e. are irrelevant distractors defined in the same feature dimension (e.g., shape, color) as the target or in a different feature dimension; third, time, i.e. how effective is distractor shielding early vs. later in processing; and finally, the incentive for effective distractor shielding.

Study 1 examined prior distractor experience and intra- vs. cross-dimensionality of distractors as factors of influence on top-down shielding from distraction. Previous research (Müller, Geyer, Zehetleitner, & Krummenacher, 2009) has shown that prior experience with distractors contributes to effective distractor shielding. Leber and Egeth (2006b) have introduced a training paradigm, which can be used to induce a feature search mode (i.e., a goal-directed search-strategy) and a singleton detection mode (i.e., a stimulus-driven search mode). Study 1 set out to connect these two lines of research: The results showed that even in feature search mode prior experience with distractors is crucial for effective distractor shielding. Furthermore, concerning intra- vs. cross-dimensionality of distractors, Study 1 investigated whether top-down distractor shielding in feature search mode is based on independent feature weighting or rather on "hierarchical" feature weighting as suggested by the so-called dimension-weighting account (e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995). It was found that observers trained to use a feature search mode were unable to prevent interference from intra-dimensional distractors, which argues against independent feature weighting in feature search mode. Instead, evidence from additional experiments argues in favor of a "hierarchical" weighting mechanism; however, this was observed unequivocally only for the shape dimension, but not for the color dimension. There may be differences in top-down distractor shielding for the various feature dimensions.

Study 2 focused on time as factor of influence on top-down distractor shielding. Previous research (e.g., van Zoest, Donk, & Theeuwes, 2004) has shown that top-down influence on saccadic target selection increases with increasing saccadic latency. That is, while early short-latency saccades are mostly stimulus-driven and, hence, favor the most salient item irrespective of task significance, later long-latency saccades are subject to top-down distractor shielding and can be reliably directed to target items even in the presence of

salient, but task-irrelevant distractors. Study 2 set out to systematically examine to which degree even early short-latency saccades can be influenced by top-down distractor shielding by means of a parametric salience difference manipulation between a target and a cross-dimensional distractor. The results showed that the amount of top-down control available already early in processing is non-negligible: When target and distractor were comparable in salience, the majority of short-latency saccades went to the target. Even when the target was somewhat less salient than the distractor, the majority of short-latency saccades could be directed to the target. Accordingly, the estimated point of equal selection probability between target and distractor was shifted to a salience difference where the distractor had a considerable bottom-up salience advantage over the target.

Study 3 investigated incentive as factor of influence on top-down shielding from distraction. Previous research (e.g., Müller et al., 2009) has shown that distractor interference is reduced if distractors appear relatively frequent as compared to relatively rare, which has been interpreted as observers having a higher incentive for distractor shielding in the former as compared to the latter case. Other research (e.g., Geng & Behrmann, 2002, 2005) has shown that target items are detected faster if they appear in a frequent target region as compared to a rare target region; a phenomenon which has been termed “probability cueing”. Study 3 tried to connect these two findings by investigating whether probability cueing can drive interference reduction for distractors in frequent distractor regions as compared to distractors in rare distractor regions (for instance, due to observers having a higher shielding incentive for frequent distractor regions compared to rare distractor regions). The results demonstrated that this is indeed the case: Distractors in a probable distractor region caused less response time slowing as compared to distractors in an improbable distractor region. Both intertrial facilitation and statistical learning were identified as underlying mechanisms of this effect: On the one hand, irrespective of statistical learning, distractor interference was reduced if a distractor appeared on the same position on two consecutive trials; on the other hand, distractor interference for distractors in frequent distractor regions was reduced compared to rare distractor regions irrespective of distractor position repetitions (i.e., even if those were restricted by the design).

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1 General Introduction

In everyday life, visual search is an omnipresent task: Looking for a certain book in the bookshelf, trying to find a friend in a crowd of people or searching for a particular product in the supermarket. However, the object one is looking for is rarely the physically most conspicuous stimulus in the environment; hence, potential distraction by salient, but irrelevant stimuli is a condition one constantly has to deal with. When an object is attentionally selected in accordance with the goals or intentions of the observer, this is usually termed "goal-directed", "endogenous", or "top-down" selection (e.g., Yantis, 1993). By contrast, when an object captures attention because of its physical salience, independent of the observer's goals or intentions, this can be termed "stimulus-driven", "exogenous" or "bottom-up" selection (e.g., Yantis, 1993). Ultimately, attentional selection is most likely neither fully stimulus-driven, nor fully goal-directed, but rather based on an interaction or combination of these two processes (e.g., Yantis, 1993); accordingly, most theories of visual attention incorporate both bottom-up and top-down components (e.g., Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Müller & Krummenacher, 2006; Navalpakkam & Itti, 2005; Wolfe, 1994). In general, whether or not a salient, but irrelevant stimulus interferes with goal-directed search, could be thought of as being dependent on the relative strengths of the bottom-up activation of the irrelevant stimulus and the top-down control settings of the observer. Under some circumstances top-down distractor shielding may be strong enough to avoid interference by salient, but irrelevant stimuli; in some cases, however, top-down distractor shielding may fail to avoid interference. This dissertation investigates several factors of influence on top-down shielding from distraction, that is, factors which play a role in determining whether or not top-down control can be strong enough to effectively avoid distraction by conspicuous, but irrelevant stimuli.

The first part of this introduction (1.1) outlines a paradigm commonly used to operationalize distraction in the study of visual attention: the additional-singleton paradigm (Theeuwes, 1992); and then goes on to summarize some relevant theories of visual attention and their stance on distraction. The second part of the introduction (1.2) describes the factors of influence on top-down shielding from distraction, which will be relevant for the main part of the thesis. The third part of the introduction (1.3), finally, outlines the aims of the thesis. Chapter 2 contains the three studies, which constitute the main part of this thesis. Chapter 3 concludes the thesis with a summarizing, comprehensive General Discussion.

1.1 Bottom-up vs. top-down control of visual attention

“Distraction” of visual attention is often operationalized in variants of the so-called “additional-singleton paradigm” (Theeuwes, 1992). In this task, observers have to search for a predefined target item surrounded by several nontarget items while in a certain proportion of trials a salient, but task-irrelevant distractor is presented in addition to the target. Since the target and the distractor compete for focal-attentional selection, “distraction” can be measured as response time interference, i.e. response time slowing in the presence compared to absence of the irrelevant distractor.

Theeuwes (1992) originally had his observers search for a shape-defined target item, while a color-defined distractor item was present in half of the trials. This caused significant distractor interference, i.e. observers were significantly slower when the distractor was present compared to absent. By contrast, when observers had to search for a color-defined target item, while a shape-defined distractor was present in half of the trials, there was no significant response time slowing. Since finding the color-defined target item was considerably faster than finding the shape-defined target item (in the no-distractor condition), Theeuwes (1992) concluded that the first one had a higher bottom-up activation (i.e., was more salient) compared to the latter one and that this should account for the observed asymmetry in the described findings. In line with this, he found that when color was made less salient and harder to discriminate (i.e., yellowish red surrounded by yellowish green nontargets compared to red surrounded by green nontargets) than shape, a shape-defined distractor interfered with search for a color-defined target, while a color-defined distractor did not interfere with search for a shape-defined target. Accordingly, Theeuwes (1992; see also Theeuwes, 1991) formulated an *automatic-attentional-capture account*, which states that preattentive parallel search cannot be influenced by top-down control to favor a specific feature or dimension. Instead, attention is automatically captured by the item with the highest local feature contrast, i.e. the most salient item, which accounts for distractor interference if the distractor is more salient than the target.

In contrast to Theeuwes’ (1992) automatic-attentional-capture account, there are various other influential theories of visual attention, which incorporate the possibility of top-down control even in preattentive parallel search. For instance, the *search-mode account* (Bacon & Egeth, 1994) offers an explanation why distractor interference can be observed under certain circumstances, but may be reduced or even absent under different circumstances. According to this account, observers can use one of two distinct search strategies, a singleton detection mode or a feature search mode, for performing visual search tasks: Visual search in singleton detection mode is completely stimulus-driven; accordingly if the target item is not the most salient item in the search display, interference by more salient (but task-irrelevant) distractors in inevitable. On the contrary, visual search in feature search mode is goal-directed, that is observers have a strong attentional set for the target-defining feature and can effectively avoid interference by all items not sharing this feature. Bacon and Egeth assume that maintaining a feature search mode may be cognitively more demanding than maintaining a singleton detection mode. This implies that if a task can be successfully accomplished in a feature search mode as well as in a singleton detection mode, observers could tend to minimize cognitive effort and prefer to operate in singleton detection mode – even if this implies accepting a slightly inferior search performance. Consequently, Bacon and Egeth hypothesized that Theeuwes (1992) might have observed strong attentional capture effects not because attentional capture is automatic and inevitable, but rather because his observers used a singleton detection mode rather than a feature search mode. To test this hypothesis, Bacon and Egeth presented their observers with visual search displays, which encouraged the use of a feature search mode: For instance, in one experiment, observers had to search for a shape-defined target while a color-defined distractor was present in half of the trials; critically, however, in one third of the trials an additional unique shape was present and in another third of the trials two additional unique shapes were present. Under those conditions, a singleton detection mode would frequently favor the wrong item, and, hence, observers were expected to use a feature search mode. In line with this, there was no significant distractor interference – not even for the one third of displays, which contained only one unique shape (i.e., the target item). Accordingly, Bacon and Egeth concluded that distractor interference can be avoided if observers are using a feature search mode.

Another account, which takes a strong stance in favor of top-down control over attentional selection, is the *contingent-attentional-capture account* (Folk et al., 1992). In one experiment, Folk and colleagues (Folk et al., 1992, Experiment 1) presented their observers with a spatial cueing paradigm, in which the actual search display was preceded by a cue display. Those cue displays contained (in different blocks of trials) either no spatial cue, a spatial cue to the center (where the upcoming target never appeared), a cue which was 100% valid for the position of the upcoming target or a cue which was 100% invalid for the position of the upcoming target. The cues were abrupt onsets; the target was for one group of observers also defined by an abrupt onset, and, for another group of observers, defined by color. Response time costs and benefits were evaluated relative to the no-cue condition. In the abrupt onset group, valid cues led to significant response time benefits, and invalid cues led to significant response time costs. While there were also significant benefits for valid cues in the color group, there were no significant costs for invalid cues in this group. This means that invalid cues only produced significant response time costs when they shared the target-defining feature, but valid cues caused significant response time benefits irrespective of whether or not they shared the target-defining feature. According to Folk et al. (1992), this pattern of results can be interpreted in terms of "contingent involuntary orienting": Depending on the task requirements, observers form an attentional set for certain stimulus properties; attentional capture by irrelevant stimuli should then be dependent on whether or not the irrelevant stimuli share the critical stimulus property or not. For instance, when looking for a color-defined target, there should be no attentional capture by irrelevant onset-defined items; when, however, looking for an onset-defined target, attentional capture by onset-defined items should not be effectively avoidable.

Guided-Search-type models of visual attention (e.g., Wolfe, 1994; Found & Müller, 1996) make up a third category of top-down models. According to them, both bottom-up and top-down components are involved in preattentive parallel search. The bottom-up component is related to salience map models (e.g., Koch & Ullman, 1985; Itti & Koch, 2000): Accordingly, bottom-up or physical salience is calculated as local feature contrast, i.e. how conspicuous or salient is an item compared to its surrounding. This local feature contrast is represented in topographic feature or dimension maps that correspond to the visual field. Those single salience maps are then summed into a master salience map, which regulates the deployment of attention. However, critically, Guided-Search-type models (e.g., Wolfe, 1994; Found & Müller, 1996) also involve a top-down component, as they assume that activity from feature or dimension maps can be weighted or scaled prior to integration into the master salience map. Hence, the activity from known-to-be-relevant feature or dimension maps can be enhanced relative to irrelevant feature or dimension maps (for instance in the case of knowing the target-defining feature in advance). Accordingly, attentional capture by a salient, but irrelevant distractor should depend on whether or not the top-down attentional weight setting is strong enough to overcome the bottom-up activation of the distractor. Note, that it is unlikely that the weight for one feature or dimension map can be set to zero, since this would imply that currently task-irrelevant, but potentially life-threatening, signals could not be detected (see e.g., Müller et al., 1995; Müller, Reimann, & Krummenacher, 2003).

1.2 Factors of influence on top-down shielding from distraction

Good theories of visual attention have to account for factors of influence on top-down shielding from distraction, i.e. why does capture occur under certain circumstances but can be prevented or reduced under different circumstances? In the following, four factors of influence on top-down shielding from distraction, which will be relevant for the main experimental part of this thesis, will be outlined: Prior experience with distractors, intra vs. cross-dimensionality of the distractor in relation to the target, time (i.e., early vs. late in processing), and, finally, distractor shielding incentive.

1.2.1 Prior experience

In several studies, prior experience has been identified as a key factor of influence on top-down distractor shielding. For instance, Leber and Egeth (2006b) trained two groups of observers to either use a feature search mode or a singleton detection mode in a classical visual search paradigm. After this training phase, both groups of observers participated in an identical test phase of so called "option trials", i.e. trials which permitted the use of both search strategies. In this test phase, the singleton detection mode observers showed significant distractor interference, while there was no distractor interference in the feature search mode group. Accordingly, it was concluded that both search groups carried over their induced search mode from the initial training phase to the test phase. Similar results of search mode carry-over were reported for a rapid serial visual presentation (RSVP) task, in which target and distractor were not presented simultaneously (as in a classical visual search task), but temporally separated (Leber & Egeth, 2006a). Using this paradigm, Leber and Egeth (2006a) also showed that the persistence of a once-established search strategy critically depends on the amount of experience you have with this search strategy. This was demonstrated by varying the length of the initial training phase: Carry-over of search mode was only observed with a sufficiently long training phase (320 trials), but not with a considerably shorter training phase (40 trials). Following up on that work, Leber, Kawahara, and Gabari (2009) showed that even after an interval of one week, a once-established search mode is reactivated when observers are presented with a similar task. Since one can reasonably assume that the induced search mode was not carried along for the whole week, the authors concluded that some aspect of the test phase triggered a reactivation of the previously induced search mode. This is in line with recent work by Cosman and Vecera (2013), who showed that, within an observer, scene contexts (forest scences vs. city scenes) could be associated with a certain search mode: In their experiment, during a training phase, singleton detection and feature search displays were always paired with a certain task-irrelevant scene context. In the subsequent test phase, observers were presented with option trials, which allowed for the use of both search modes. However, each of these displays was randomly presented within a scene, which had been paired with either feature search mode or singleton detection mode during the training phase. In line with the idea that context can reactivate an associated search mode, in the test phase, distractor interference was only present for displays embedded in a scene context previously associated with a singleton detection mode, but not for displays embedded in the feature search mode scene context.

Müller et al. (2009) have suggested that distractor experience per se, rather than learning to handle distractors in a certain search mode, is a critical factor for top-down shielding from distraction. According to them, the acquisition of a top-down shielding strategy during practice is a key factor for effective distractor shielding. This was, among others, tested in an experiment (Müller et al., 2009, Experiment 2), in which groups of observers received different practice blocks before the measurement of distractor interference effects: Half of the observers consistently encountered irrelevant distractors during the practice block (100% distractor prevalence), whereas the other half of the observers never encountered distractors during the practice block (0% distractor prevalence). In line with the idea that observers in the 100% distractor groups had the opportunity to acquire a distractor shielding strategy, while observers in the 0% distractor groups did not, the 100 % groups exhibited subsequent reduced distractor interference compared to the 0% groups. According to the *dimension-weighting account* (e.g., Found & Müller, 1996; Müller et al., 1995; Müller et al., 2003) distractor shielding is achieved by increasing the top-down weight for the target-defining dimension or by decreasing the top-down weight for the distractor-defining dimension. Müller et al. (2009) speculated that distractor practice could be a critical factor for distractor shielding because, during practice, observers might learn to optimally tune the weight distribution for the target and distractor dimensions.

Prior experience can also contribute to distractor interference reduction on a more short-term time scale: For instance, Müller et al. (2009) found interference to be attenuated following distractor-present trials compared to distractor-absent trials (see also Geyer, Müller, & Krummenacher, 2008; Zehetleitner, Proulx, & Müller, 2009). This was interpreted as observers, who recently shielded against a distractor, carrying over this shielding routine to the next trial (or having it more readily available on the next trial). For instance, framed in terms of the dimension-weighting idea, observers would down-modulate the weight assigned to the irrelevant distractor dimension (or feature) after encountering a distractor defined in that dimension (or by that feature). Accordingly, on the next trial, a distractor defined by that dimension (or feature) would cause comparably less activation on the master salience map, which guides attentional selection, and, hence would lead to less distractor interference.[1] Intertrial distractor shielding effects of this kind are also in line with various findings from research on cognitive control processes and their role in the resolving of response conflict: Interference from response incongruent stimuli is reduced if response conflict was present, as compared to absent, on the previous trial (e.g., flanker task: Gratton, Coles, & Donchin, 1992; Stroop task: Kerns et al., 2004; Simon task: Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). These effects have often been interpreted in terms of "conflict monitoring" (Botvinick, Braver, Barch, Carter, & Cohen, 2001). According to this prominent theory, the anterior cingulate cortex detects conflict on a given trial and thereupon engages the recruitment of additional cognitive control, which modulates performance on subsequent trials: The recruited cognitive control on the current trial n is larger when conflict was encountered on the preceding trial n-1, compared to when no conflict was encountered – which predicts interference to be smaller on trials following conflict trials compared to trials following non-conflict trials.

1.2.2 Intra- vs. cross-dimensionality

In addition to being influenced by prior experience, there is reason to assume that distractor shielding may differ depending on whether the distractor item is defined in the same or in a different dimension than the target item. For instance, when looking for a shape-defined target, it might be easier to shield against interference from a color-defined (cross-dimensional) distractor compared to interference from a shape-defined (intra-dimensional) distractor. Theoretically, this claim can be derived from the *dimension-weighting account* (e.g., Found & Müller, 1996; Müller et al., 1995; Müller et al., 2003) according to which the weighting of features and dimensions is hierarchically organized with the result that the weighting of a particular feature will always bring along an increased weighting of the whole feature dimension compared to other feature dimensions. Consequently, if observers are presented with a target and a distractor defined in the same dimension, distractor interference should not be effectively preventable: By assigning weight to the target-defining feature, the

[1] Note however that these n-1 effects were dependent on the overall distractor frequency: That is, they were more pronounced or only present if distractors were relatively rare (Geyer et al., 2008; Müller et al., 2009). This might be due to observers in higher distractor frequency conditions applying more top-down control in general (e.g., due to having an overall higher incentive for top-down distractor shielding, see 1.2.4). If distractor shielding is already comparably high, there is less possibility for additional interference reduction effects.

weight of any distractor defined by another feature in the same dimension would also be increased; although, depending on the strength of the hierarchical coupling, not necessarily to the same degree as the target weight. Accordingly, there would be two activation peaks on the master salience map, and the distractor would be processed with priority in a certain proportion of trials, inevitably causing interference.

Empirical support for this notion comes for instance from Kumada (1999), who had his observers search for orientation-defined target items (rectangles tilted 45° to the left relative to vertical nontargets) and presented them with intra-dimensional distractors. These distractors were (in different experiments) either equally salient as the target (rectangles tilted 45° to the right) or less salient than the target (rectangles tilted 22.5° to the right). In a simple search task (where observers had to indicate the presence vs. absence of the target item), both the equally salient and the less salient intra-dimensional distractor caused significant response time slowing (see van Zoest & Donk, 2004, for similar results). These results were replicated in two experiments with compound search tasks (where observers had to indicate the location of a line segment intersecting the target item): A distractor tilted 45° to the right significantly interfered with search for a target tilted 45° to the left. The finding of less salient intra-dimensional distractors causing response time slowing was replicated within the color dimension: For two groups of observers the target item was either a red rectangle, and the distractor a green rectangle (surrounded by gray nontargets), or the other way around. Since response times for the green target (in the no-distractor condition) were significantly faster than response times for the red target (in the no-distractor condition), it can be concluded that the green feature contrast was higher compared to the red feature contrast. Despite that, there was significant distractor interference in both search groups; again, suggesting that if target and distractor are defined within the same dimension, distractor shielding cannot even avoid interference by distractors less salient than the target.[2]

1.2.3 Time

Another important factor of influence on top-down shielding from distraction is "time": For instance, according to the current version of the *automatic-attentional-capture account* (Theeuwes, 2010), attentional selection is initially completely driven by the bottom-up factors of the environment. Hence, the first location to be selected rather automatically is the

[2] Kumada (1999) also investigated interference for cross-dimensional distractors: In a simple search task, he did not observe any distractor interference effect. By contrast, using a compound search task – as Theeuwes (1992) did -, Kumada observed a significant interference effect by a cross-dimensional distractor, but only if the distractor was more salient than the target.

one with the highest salience or feature contrast ("attentional capture"). Only later in processing, i.e. time, top-down control comes into play by influencing the speed of attentional disengagement from the selected item. Strong support for this notion comes from Theeuwes, Atchley, and Kramer (2000), who presented their observers with a variant of the classical additional-singleton paradigm (Theeuwes, 1992): The task was to search for a shape-defined target item, while a color-defined distractor item was present in some trials. Critically, the distractor item appeared at different stimulus-onset asynchronies (SOAs) before the presentation of the remaining search display. The results showed that there was no distractor interference effect, when the distractor was presented 150 ms (or longer) before the search display. It was concluded that while the color distractor captured attention early in processing, attentional capture could be overcome later in time by top-down control.

Another theory, which emphasizes the importance of time in top-down shielding from distraction is the *timing account* of visual selection (e.g., van Zoest et al., 2004): Van Zoest et al. (2004) employed a saccadic selection variant of the classical additional-singleton paradigm (Theeuwes, 1992), in which observers were asked to make a speeded saccade towards a known target item, while a salient, but irrelevant distractor item was likewise present in the search display. Across several experiments, they observed that the proportion of correct target saccades increased with increasing saccadic latency, i.e. observers made more correct target fixations, the slower the eye movements were initiated. When target and distractor were comparable in salience (e.g. tilted 45° to the left or to the right relative to vertical nontargets), they also attracted an equal amount of early (i.e., short-latency) saccades; only later in time (i.e., with increasing saccadic latency) were observers able to direct more saccades to the target in comparison to the equally salient distractor. Based on these findings, van Zoest et al. (2004) concluded that "saccadic visual selection is initially completely stimulus driven", whereas "later in time, goal-driven control dominates visual selection" (p. 755). Several subsequent studies by van Zoest and Donk (e.g., 2005, 2006, 2008) provided further empirical support for this view; however, van Zoest and Donk (2008) departed slightly from the strong original conclusion that saccadic visual selection is initially completely determined by bottom-up factors and acknowledged some limited top-down selectivity even early in time.

1.2.4 Shielding incentive

Finally, Müller et al. (2009) proposed that top-down shielding from distraction is also influenced by the incentive for distractor shielding. Müller and colleagues operationalized shielding incentive as distractor prevalence: If distractors appear in a high proportion of trials, i.e., potentially capturing attention rather often, observers should have a comparably higher incentive to minimize interference by those distractors. By contrast, if distractors appear only in a low proportion of trials, observers might be more willing to tolerate the little interference those distractors might cause – especially considering that distractor shielding is probably an effortful process. In line with this, Müller et al. (2009) observed more pronounced response time interference effects in trial blocks with a higher distractor prevalence and comparably smaller interference effects in blocks with a lower distractor prevalence (see also Forster & Lavie, 2008, and Zehetleitner et al., 2009, for similar results).

Similar results were reported by Geyer, Müller, and Krummenacher (2008), who not only measured manual response times, but also eye movements: In their experiment, the presence of a salient, but irrelevant distractor, led to increased saccadic latencies compared to the distractor-absent condition – however, only if distractors were rather infrequent, i.e., when the shielding incentive was low. In addition, (erroneous) distractor fixations occurred more often if distractors were infrequent compared to frequent. Sayim, Grubert, Herzog, and Krummenacher (2010) used onset (rather than static) distractors and likewise observed a decreasing percentage of saccades captured by the distractor, the higher the proportion of onset distractors within a block.

Distractor prevalence effects can also be accounted for by the conflict monitoring model (Botvinick et al., 2001) previously introduced (see 1.2.1): One core assumption of this model is that the recruited cognitive control, rather than decaying immediately after the next trial, is carried along some time – and, so, does not only influence performance on the immediately following trial, but also on subsequent trials. Therefore, if conflict trials are frequent, the recruited cognitive control accumulates and, thus, reduces the overall interference effect, compared to when conflict trials are rare.

1.3 Aims of the thesis

Good and comprehensive theories of visual attention have to be able to account for the various factors of influence on top-down shielding from distraction. For theories of visual attention to be able to incorporate such factors of influence, it is necessary to understand those factors as comprehensively as possible. The present dissertation set out to close several knowledge gaps about the aforementioned factors of influence: For instance, as outlined above, there is evidence suggesting that top-down shielding from distraction is more effective with prior distractor experience (e.g., Müller et al., 2009) and with cross-dimensional compared to intra-dimensional distractors (e.g., Kumada, 1999). However, it is yet unknown, whether these two factors of influence are also relevant when observers are using a goal-directed search strategy, i.e., a feature search mode. Gaining such information will be helpful in evaluating the search-mode account (e.g., Bacon & Egeth, 1994) and its associated idea of two distinct search modes. Similarly, previous research has shown that top-down distractor shielding is more effective later in time than early in time. However, little is known about the magnitude of early top-down control. Estimating the magnitude of early top-down control is, among other things, important to evaluate the claim that attentional selection is initially completely driven by the bottom-up factors of the environment, as suggested by the current version of the automatic-attentional-capture account (Theeuwes, 2010). Finally, previous research has shown that top-down distractor shielding is more effective if observers have a higher shielding incentive, i.e., distractor interference is reduced if distractors appear frequently as compared to rarely (e.g., Müller et al., 2009). Yet it is still unknown, whether a shielding incentive of this kind can also be “fine-tuned” to specific distractor areas (which frequently contain distractors) and what the underlying mechanism of such a fine-tuning could be. Investigating this possibility is potentially relevant for Guided-Search-type models of visual attention (e.g., Wolfe, 1994; Found & Müller, 1996), since the existence of such a location-specific shielding mechanism would suggest that top-down feature- or dimension weighting could also involve a spatial component. Taken together, the present dissertation set out to specify present knowledge about factors of influence on top-down shielding from distraction, thus providing potentially relevant information for current theories of visual attention.

Study 1 set out to investigate both prior experience (see 1.2.1) and intra- vs. cross-dimensionality of distractors (see 1.2.2) as factors of influence on top-down shielding from distraction. Concerning the former, the main aim of Study 1 was to examine the contribution of prior experience with distractors to distractor shielding effects, which have previously been interpreted in terms of the acquisition of different search modes: As has been previously discussed (see 1.2.1), Leber and Egeth (2006b) had shown that observers trained to use a feature search mode, carried this search mode over to a test phase with so-called “option-trials” (allowing for the use of both a feature search mode and a singleton detection mode) and thus, were able to completely prevent distractor interference in this test phase. However, critically, in the feature search training phase of Leber and Egeth (2006b) distractors were present in half of the trials; accordingly, those observers also had prior experience with distractors, which, according to Müller et al. (2009), may be a critical factor for effective top-down distractor shielding. Hence, Study 1 set out to investigate whether prior distractor experience is a prerequisite for effective distractor shielding in feature search mode. To this end, Experiment 1 of Study 1 was a replication of the search mode training paradigm of Leber and Egeth (2006b), while Experiment 2 modified the paradigm in so far as no distractors were shown during the training phase, which was supposed to induce the respective search modes (feature search mode and singleton detection mode). If prior experience with distractors is crucial for effective interference reduction in feature search mode, the feature search group of Experiment 1 should be able to avoid distractor interference, while the feature search group of Experiment 2 should not be able to do so.

Concerning intra- vs. cross-dimensionality of distractors, the main aim of Study 1 was to investigate whether top-down distractor shielding in feature search mode is based on independent feature weighting (i.e., each feature can be weighted independently of all other features) or “hierarchical” feature weighting (as suggested by the dimension-weighting account, e.g., Müller et al., 2003; see 1.2.2). If top-down distractor shielding in feature search mode were based on independent feature weighting, observers in feature search mode should be able to avoid or minimize interference by intra-dimensional distractors just as effectively as interference by cross-dimensional distractors. As has been previously discussed (see 1.2.2), there is evidence that top-down shielding from distraction is not as effective with intra- compared to cross-dimensional distractors (e.g., Kumada, 1999); however, those findings may be vulnerable to the criticism that observers did not use a feature search mode, but instead a singleton detection mode, and therefore could not effectively avoid distractor interference. To challenge this criticism, observers in Experiment 3 of Study 1 were trained to use a feature search mode prior to being confronted with intra-dimensional distractors. If independent feature weighting in feature search mode were possible, observers trained to use a feature search mode should be able to avoid interference by intra-dimensional distractors. Experiments 4 and 5 set out to more positively test the idea of hierarchical feature weighting: To this end, observers again underwent a training and test phase, with cross-dimensional distractors present during both phases, however, the distractor-defining feature changed from the training to the test phase (within one feature dimension). If top-down distractor shielding were based on hierarchical feature weighting, prior experience with one distractor feature should facilitate top-down distractor shielding against another distractor feature of the same dimension.

Study 2 focused on time (see 1.2.3) as factor of influence on top-down shielding from distraction: The *timing account* of visual selection (e.g., van Zoest et al., 2004) suggests that early visual selection is mostly stimulus-driven, whereas later in selection goal-directed control takes over; accordingly, when observers are asked to make an eye movement to a target item, while a salient, but irrelevant distractor item is present at the same time, the vast majority of early (short-latency) eye movements should go to the salient distractor, and only later (long-latency) eye movements should be successfully guidable to the target. This pattern of results has been demonstrated repeatedly (e.g., van Zoest et al., 2004; van Zoest & Donk, 2005, 2006, 2008). The aim of Study 2 was to systematically investigate to which degree even early (short-latency) eye movements can be subject to top-down guidance.

To this end, the salience difference between a target item and a cross-dimensional distractor was parametrically manipulated, which allowed to examine percentage (early) target and distractor fixations as a function of the salience difference between target and distractor. Salience difference was estimated (in a separate experiment) as the difference in detection response times between the target feature and the distractor features (see Zehetleitner, Koch, Goschy, & Müller, 2013, for a similar salience estimation procedure): The faster the distractor feature was detected by comparison to the target feature, the more salient by comparison to the target feature it was assumed to be; distractor features, which were detected equally fast as the target feature, were assumed to be of comparable salience.

When examining percentage target and distractor fixations as a function of their parametric salience difference, a pure bottom-up account of early saccadic target selection and a top-down account of early saccadic target selection make divergent predictions; this allows for a comparison of these two accounts: First, percentage target and distractor fixations for a salience difference close to zero were analyzed. In this case, target and distractor should be of comparable salience. Hence, according to a pure bottom-up account of early saccadic target selection, both target and distractor should attract an equal amount of early fixations (50% : 50%).[3] On the contrary, according to a top-down account of early saccadic target selection, the target should have an increased selection probability and, thus, attract more early fixations than the distractor. Second, the percentage fixation distributions for distractors more salient than the target were analyzed: If early saccadic target selection

[3] As previously discussed (see 1.2.3), van Zoest et al. (2004) did in fact observe an equal amount of early target and distractor fixations, if target and distractor were of comparable salience. However, in this case, target and distractor were both defined by orientation, i.e. in the same dimension. Shielding against distractors defined in the target dimension might differ from shielding against cross-dimensional distractors (see 1.2.2).

were purely bottom-up, distractors more salient than the target should always attract more early fixations than the target. By contrast, if there were top-down control over early saccadic target selection, it should be able to overcome a certain bottom-up salience advantage of the distractor: Hence, if the target is only somewhat less salient than the distractor, it should still be able to attract more early fixations than the distractor. Third, the salience difference point of equal selection probability (for target and distractor) was estimated: According to a pure bottom-up account of early saccadic target selection, target and distractor should have a comparable selection probability if they are of comparable salience. However, if the estimated point of equal selection probability is shifted to a salience difference at which the distractor is more salient than the target, this is a strong (even quantitative) indicator for early top-down control over saccadic target selection.

Study 3 was concerned with the question whether the observers' "shielding incentive" (see 1.2.4) can also be fine-tuned to specific distractor locations: I.e., if distractors appear comparably frequently in a certain region of the visual field, can observers selectively suppress interference from distractors appearing in this area of the visual field? If this were the case, interference by distractors appearing in frequent distractor regions should be reduced compared to distractors appearing in rare distractor locations.

A similar question was investigated by Reder, Weber, Shang, and Vanyukov (2003) in a target localization paradigm, in which observers had to indicate which of four locations contained a target item, while a distractor item could be present at the same time at one of the other locations. While the target item appeared equally often at each of these four locations, the distractor item was not equally probable at these locations. This manipulation affected the response times: Distractors at frequent locations caused essentially no response time slowing, whereas distractors appearing at rare locations led to substantial slowing.

The aim of Experiment 1 of Study 3, was to examine whether such "fine-tuned" distractor shielding can also be observed in a classical additional-singleton paradigm and whether it can also be applied to (frequent or rare) distractor areas rather than single (frequent or rare) distractor positions (as in Reder et al., 2003). The aim of Experiments 2 and 3 was to examine what might cause such fine-tuned distractor shielding, which was not systematically examined by Reder et al. (2003). Research on the so-called "probability cueing effect" for target locations has shown that objects at probable locations are detected or discriminated faster as compared to objects at less probable locations (e.g., Druker & Anderson, 2010; Fecteau, Korjoukov, & Roelfsema, 2009; Geng & Behrmann, 2002, 2005;

Shaw & Shaw, 1977). Traditionally, this effect has been attributed to “statistical learning”, i.e. the formation of location-specific stimulus expectancies over a longer sequence of trials (e.g., Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Hoffmann & Kunde, 1999). However, if a target is more likely to appear in a certain location, target position repetitions in this location are also more frequent compared to a location where the target is less likely to appear. Hence, Walthew and Gilchrist (2006) have suggested that the probability cueing effect might also be attributable to intertrial facilitation due to target position repetitions: A vast amount of research has shown that repeating the target position on consecutive trials leads to faster response times compared to changing the target position (e.g., Geyer, Zehetleitner, & Müller, 2010; Kristjánsson, Vuilleumier, Schwartz, Macaluso, & Driver, 2007; Kumada & Humphreys, 2002; Maljkovic & Nakayama, 1996).

Accordingly, Experiments 2 and 3 of Study 3 set out to transfer these findings to the probability cueing effect for distractor locations: In Experiment 2, it was investigated whether intertrial facilitation (irrespective of statistical learning) can contribute to distractor interference reduction, that is, is it easier to prevent interference by a distractor, which reappears at a just recently encountered distractor position? In Experiment 3, it was investigated whether statistical learning can also contribute to interference reduction, if there are no distractor position repetitions. Note that it is also possible that both intertrial facilitation and statistical learning contribute to probability cueing (see also Kabata & Matsumoto, 2012).

2 Cumulative Thesis

This cumulative thesis consists of three individual studies: Two peer-reviewed and published articles (2.1 and 2.2) and one submitted manuscript (2.3). The following chapter encloses these studies, each accompanied by a short summary and a statement concerning the contributions of the involved authors.

2.1 Top-down control of attention:
It's gradual, practice-dependent, and hierarchically organized

SUMMARY

Leber and Egeth (2006b) have developed a training paradigm, which can be used to induce different search modes: In this paradigm, observers trained to use either a feature search mode or a singleton detection mode during a training phase, carry over this search mode to a test phase, where both search modes would be applicable. In the first study presented in this dissertation, this training paradigm was utilized, to investigate the contribution of distractor practice to distractor shielding in feature search mode and the specificity of distractor shielding in feature search mode, that is, are there differences in shielding against intra-dimensional distractors (i.e., distractors defined in the same dimension as the target) compared to cross-dimensional distractors (i.e., distractors defined in a different dimension than the target)? Experiment 1 replicated the results of Leber and Egeth (2006b): Observers trained to use a feature search mode during a training phase did not show any distractor interference during a subsequent test phase, while observers trained to use a singleton detection mode during a training phase, could not effectively prevent distractor interference during the subsequent test phase. Experiment 2 was a modification of Experiment 1, in which there were no distractors shown during the training phases: Under those circumstances, both search mode groups were unable to avoid distractor interference during the subsequent test phase. This demonstrates that, even in feature search mode, distractor practice is essential for effective distractor shielding.

Experiment 3 investigated whether observers trained to use a feature search mode could effectively shield against intra-dimensional distractors presented in the subsequent test phase. This was not the case: Observers trained to use a feature search mode were as unable as singleton detection mode observers to prevent interference by intra-dimensional distractors. This suggests that top-down distractor shielding in feature search mode is not based on independent feature weighting, which allows for the weighting of one feature irrespective of all other features of the same dimension. Experiments 4 and 5 set out to test an alternative hypothesis of "hierarchical" feature weighting or "dimension weighting" (e.g., Found & Müller, 1996; Müller et al., 1995). According to this idea, features within a dimension are hierarchically "coupled" in so far that the weighting of a feature within a certain dimension, will also affect other features defined in this dimension. Experiments 4 and 5 presented

cross-dimensional distractors with the distractor-defining feature changing from the training to the test phase. If top-down distractor shielding were based on hierarchical feature weighting, distractor practice with one distractor feature should facilitate distractor shielding against another distractor defined in the same distractor dimension. In Experiment 4, color-defined distractors were presented (in addition to a shape-defined target); distractors in the training phase were orange, while distractors in the test phase were pink. However, feature search mode observers were unable to utilize distractor practice with the orange training phase distractor to effectively shield against the pink test phase distractor. In Experiment 5, shape-defined distractors were presented (in addition to a color-defined target); distractors in the training phase were squares, while distractors in the test phase were diamonds. By contrast to Experiment 4, feature search mode observers could utilize distractor practice with the square training phase distractor to effectively avoid distractor interference by the diamond test phase distractor. Taken together, the present results are difficult to reconcile with the idea of independent feature weighting. Instead, they suggest a hierarchical weighting structure – at least for the shape dimension, but not necessarily for the color dimension. This suggests that weighting structures might differ between various feature dimensions (e.g., between color and shape).

CONTRIBUTIONS

HG and MZ share first authorship. Parts of the experimental work for this study were done in the context of the diploma thesis project of **HG**, which was supervised by MZ. **HG** and MZ conceived and designed the experiments. **HG** collected and analyzed the data. **HG** discussed the results with MZ and HJM. **HG**, MZ, and HJM wrote the paper.

REFERENCE

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Top-down control of attention:

It's gradual, practice-dependent, and hierarchically organized

Michael Zehetleitner*

Ludwig-Maximilians-Universität München, Munich, Germany

Harriet Goschy*

Graduate School of Systemic Neurosciences, Ludwig-Maximilians-Universität München, Munich, Germany

Hermann J. Müller

Ludwig-Maximilians-Universität München, Munich, Germany, and

Birkbeck College, University of London, London, UK

* Contributed equally to this article.

ABSTRACT

When searching for a 'pop-out' target, interference from a salient but irrelevant distractor can be reduced or even prevented under certain circumstances. Here, five experiments were conducted to further our understanding of three different aspects of top-down interference reduction: first, whether or not qualitatively different search modes can account for different reduction patterns; second, whether distractor practice plays a causal role in reduction; and third, how specific reduction is, that is, whether interference by intra-dimensional distractors can be reduced as effectively as interference by cross-dimensional distractors. The results provide evidence that interference reduction does not critically depend on the implement-tation of a feature search mode, but rather on practice with the distractor, that is, the acquisition of an effective suppression strategy. In addition, they suggest that interference reduction is based on hierarchically organized feature weighting ('dimension weighting'), rather than on completely independent feature weighting.

INTRODUCTION

Most current theories of visual search take the possibility of top-down control over the allocation of attention into consideration (e.g., Folk, Remington, & Johnston, 1992; Bacon & Egeth, 1994; Wolfe, 1994; Navalpakkam & Itti, 2005; Müller & Krummenacher, 2006; Zehetleitner, Krummenacher, Geyer, Hegenloh, & Müller, 2011). According to these accounts, by applying top-down control, bottom-up salience calculations can be modulated in accordance with the behavioral goals of the observer, which has the potential to attenuate attentional capture by distracting objects. Attentional capture is usually measured as response time (RT) slowing in the presence, compared to the absence, of a distracting object (distractor 'interference'). Indeed, various studies have shown that interference by salient but irrelevant singletons can be reduced or even prevented under certain circumstances (e.g., Bacon & Egeth, 1994; Leber & Egeth, 2006a, 2006b; Müller, Geyer, Zehetleitner, & Krummenacher, 2009). However, what remains controversial is how top-down control actually works. The present study focuses on three issues of how top-down control reduces interference in visual search, which are currently under debate: (i) Are there qualitatively different search modes? (ii) What is the contribution of practice? (iii) What is the specificity of top-down control?

Are there qualitatively different search modes?

One proposal that has become prominent to explain why distractor interference does occur under some conditions, but can be reduced or prevented under others, is the notion of differential ‘search modes’. The search-mode account, initially proposed by Bacon and Egeth (1994; see also Pashler, 1988), assumes that there are two distinct strategies, or processing modes, for performing visual search tasks: a singleton detection mode and a feature search mode (in the following shortly referred to as ‘singleton mode’ and ‘feature mode’). Observers operating in singleton mode automatically allocate attention to the item generating the highest local salience (feature contrast) signal; that is, search is stimulus-driven. Consequently, interference is unavoidable if the target is not the most salient item. By contrast, observers using a feature mode have a fixed attentional set for the (known) target-defining feature, preventing interference by all features not matching this set. Thus, according to the search-mode account, the operation of a feature mode is the causal mechanism underlying interference reduction.

Strong support for this idea comes from findings of divergent patterns of distractor interference under induced singleton and feature modes (Leber & Egeth, 2006a, 2006b). In addition, the same studies have provided evidence that, once established, the different search modes are used persistently even in the face of small task changes. Recently, Leber, Kawahara, and Gabari (2009) showed that even after an interval of one week, observers reactivated an established search mode when presented with a similar task.

Note, however, that there are two possible ways in which a feature mode could be realized (see also Figure 1a): On the one hand, attentional selection could be based directly on the relevant target feature map (e.g., Treisman & Souther, 1985; Pashler, 1988; see also Bravo & Nakayama, 1992). In this case, activity in all other feature maps would be ignored and distractors not sharing the target-defining feature would have no capacity at all for capturing attention. On the other hand, attentional selection could be based on a master salience map composed of the activity from various feature maps (e.g., Koch & Ullman, 1985; Itti & Koch, 2000). In this case, observers would top-down assign a high weight to a particular feature they are interested in, while scaling down the weighting for all other features (e.g., Wolfe, 1994; Navalpakkam & Itti, 2005). On the first, *architectural* version of the feature mode, interference reduction would work in a binary/discrete (all-or-nothing) fashion, while on the second, *weighting* version, the strength of top-down weights to a specific feature can be modulated continuously. Although a similar distinction has already been put forward by Bacon and Egeth (1994, p. 487), the literature building on their work has, by and large, made little effort to differentiate between these alternatives.

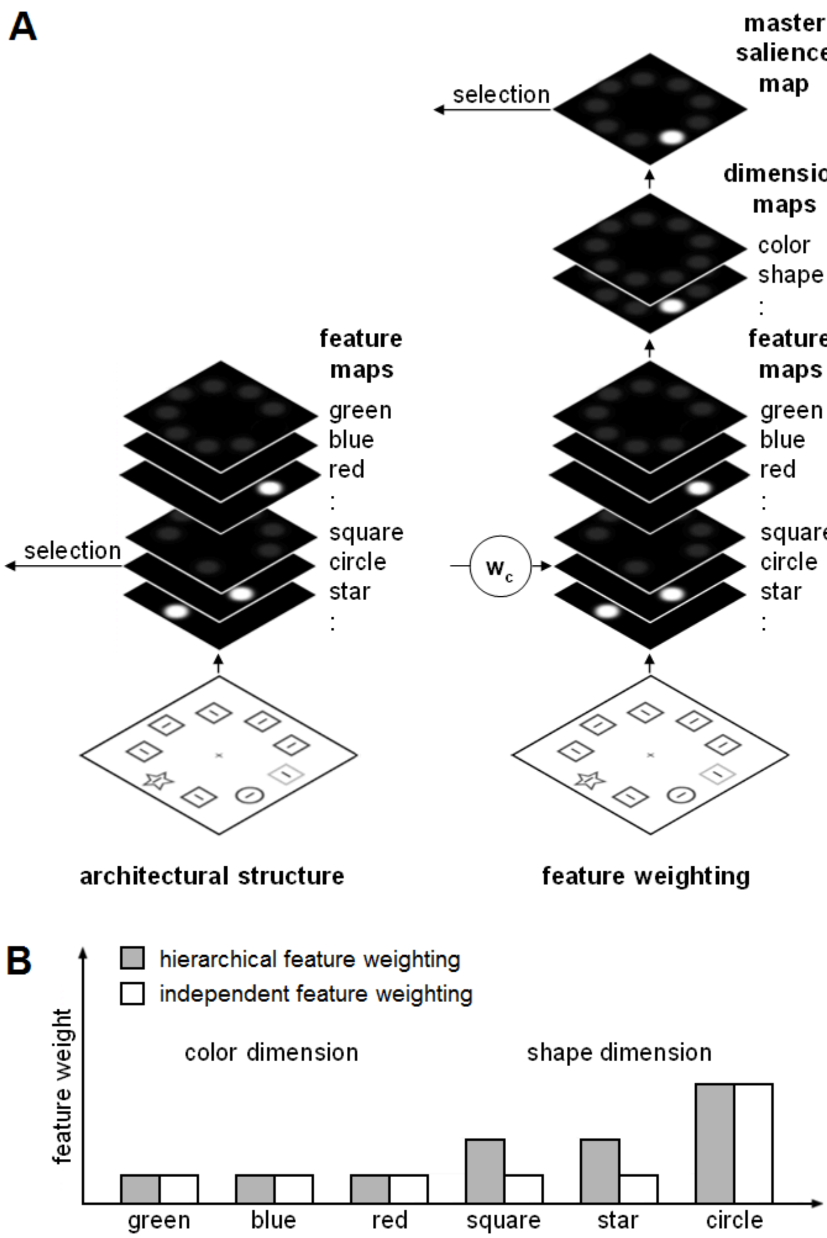

Figure 1. (A) Schematic representation of two architectures that can realize the feature mode: In the *architectural* structure (left), attentional selection is based solely on the relevant feature map. In the *feature weighting* structure, attentional selection is based on a master salience map. (B) Representation of two possible implementations of the weighting strategy: one in which all feature weights are independent of each other (parallel organization), and one in which the feature weights are hierarchically organized. – The depicted search display is a hypothetical example not used in the present experiments: The target would be a green circle surrounded by green squares. In addition, there are two distractors present: a green star defined in the same dimension as the target and a red square defined in a different dimension. According to a strong architectural interpretation of the feature mode (A, left), attentional selection is based on the relevant target feature map (circle map). As neither the intra- nor the cross-dimensional distractor cause any activation in this feature map, attentional capture can be completely prevented, that is, interference reduction works in a binary (on/off) fashion. By contrast, according to a feature weighting interpretation of the feature mode (A, center), observers assign weight to the target feature

map (circle: w_c), which leads to an increased activation of the weighted feature signal (relative to the unweighted feature signals) on the master salience map. Attentional capture is therefore dependent on the amount of exerted feature weighting: If the target weighting is strong enough to outweigh the bottom-up activation of the distractor features (as in the example depicted), distractor interference would be completely prevented. Note that on this assumption of independent feature weighting, both the weighting of the intra- and the cross-dimensional distractor can be reduced to a similar degree (B, independent feature weighting). In contrast, given a hierarchically organized feature weighting structure as proposed by the dimension-weighting account (B, hierarchical feature weighting), weighting of the target feature (circle: w_c) will automatically increase the weighting of other features within the same dimension (compared to features of other dimensions). Accordingly and depending on the strength of the hierarchical weight coupling, interference reduction for intra-dimensional distractors cannot be achieved as effectively as for cross-dimensional distractors.

In more detail, findings of interference reduction previously attributed to qualitatively different search modes can also be explained by a continuum of top-down control as suggested by Guided-Search-type models (e.g. Wolfe, Cave, & Franzel, 1989; Wolfe, 1994; Müller, Heller, & Ziegler, 1995; Found & Müller, 1996, Navalpakkam & Itti, 2005). These models assume a single processing route with a two-stage architecture: In the first, preattentive, parallel stage, local salience-based feature contrast signals are calculated, which can be top-down modulated or 'weighted' prior to their integration into the master salience map, which regulates access to the second, limited-capacity stage required for more complex operations, such as object identification (Müller & Krummenacher, 2006; Zehetleitner, Proulx, & Müller, 2009; Zehetleitner, Krummenacher, & Müller, 2009; Zehetleitner, Krummenacher, et al., 2011). Accordingly, whether or not interference by salient but task-irrelevant distractors can be down-regulated should not depend on the application of a certain search mode, but rather on the top-down weight setting on a given trial (i.e., whether or not it is strong enough to overcome the bottom-up activation generated by a salient distractor).

Such a continuum of top-down control would be more in line with several findings that are hard to reconcile with the assumption of stable, 'categorical' search modes. For instance, Müller et al. (2009) described task conditions in which interference varied substantially depending on the presence versus the absence of a distractor on the previous trial. Similarly, Leber (2010) found interference to fluctuate despite consistent experimental conditions, which led him to conclude that there is a continuum of top-down control, rather than search behavior being either purely stimulus- or purely goal-driven. Finally, Lamy and colleagues (Lamy, Carmel, Egeth, & Leber, 2006; Lamy & Yashar, 2008) found interference to be larger in fixed-singleton search (in which the target-defining feature is the same on every trial) compared to mixed-singleton search (in which the target feature changes unpredictably from trial to trial within the same dimension) – at variance with the search-mode account, on which a salience-based strategy should have been used in both tasks. This finding led Lamy and colleagues to question the notion of a distinct singleton mode that is solely reliant on stimulus salience. On this background, the first issue to be examined is whether there are qualitatively different search modes, and, if so, whether interference reduction in feature mode works in an all-or-nothing fashion or whether there is a continuum of how strongly bottom-up signals are modulated by feature-based top-down weighting.

What is the contribution of practice?

If observers are capable of reducing the interference caused by salient but task-irrelevant distractors, one central question is: why do they not always choose to do so? Recent findings indicate that the extent to which top-down control is applied depends both on the incentive to do so (provided by the task) and on practice in dealing with the distractor. Attentional capture, by a distractor that is defined in another dimension and physically more salient than the target, varies in magnitude as a function of distractor prevalence, with relatively little interference when distractors are frequent (thus providing a high incentive for suppression) and pronounced interference when distractors are rare (providing a low suppression incentive; Müller et al., 2009; Geyer, Müller, & Krummenacher, 2008; Zehetleitner, Proulx, & Müller, 2009; Forster & Lavie, 2008). In addition, observers who consistently encountered, relative to observers who never encountered, distractors in a practice block before the measurement of interference showed reduced distractor interference – arguably attributable to the fact that they had the opportunity to acquire a suppression strategy (Müller et al., 2009). Following up these findings, the second question to be examined concerns the contribution of distractor practice to effects of interference reduction, that had previously been attributed solely to the acquisition of different search modes.

What is the specificity of top-down control?

When an observer is interested in one specific feature – for instance, the shape feature ‘circle’ – how specifically is top-down control tuned to that particular feature, as compared to other features within the same dimension (e.g., ‘square’) or features in other dimensions (e.g., ‘red’)? Both the architectural and the weighting-based interpretation of the feature mode assume that relevant features can be selected or modulated independently of other features (see Figure 1b). Accordingly, the prediction is that effective interference reduction is possible even with distractors defined in the same dimension as but by a different feature to the target.

By contrast, there is an alternative account, which assumes that feature-specific top-down control has a differential impact on other features of the same or of different dimensions. This idea is spelled out in detail in the dimension-weighting account (e.g., Müller et al., 1995; Found & Müller, 1996), which is essentially an extension of the Guided-Search model (e.g., Wolfe, Cave, & Franzel, 1989; Wolfe, 1994). It assumes that the weighting of features and dimensions is hierarchically organized, such that the weighting of a particular feature will always involve an increased weighting of all features defined in the same dimension compared to features of other dimensions (see also Figure 1b). This idea of top-down 'hierarchical feature weighting' is supported by results of a trial-by-trial symbolic pre-cueing experiment (Müller, Reimann, & Krummenacher, 2003; see also Zehetleitner, Krummenacher, et al., 2011; Zehetleitner, Hegenloh, & Müller, 2011): the cueing benefits in this experiment were comparable regardless of whether the target was actually defined by the cued feature or rather by another feature in the same dimension; for example, when observers, in response to the cue word 'red', prepared for a target defined by the color red (79% cue validity), a blue target (with a 7% likelihood) was detected almost as fast as the cued target, but faster than a target defined by left- or right-tilted orientation (each with a 7% likelihood). Similarly, Meeter and Theeuwes (2006) reported that cueing the target identity not only speeded up target detection, but also influenced distractor interference: distractors defined in the cued dimension (but by another feature) caused larger interference as distractors defined in another dimension (see also Schubö & Müller, 2009, for electro-physiological evidence of differential processing of intra- vs. cross-dimensional distractors).

Note that 'hierarchical feature weighing' does not preclude the possibility of feature weighting. Rather, according to this notion, features within one dimension cannot be weighted completely independently of one another: an increased weighting for 'circle' will also increase the weighting of other shape features (e.g. 'square', 'star'), compared to color features (e.g. 'red', 'blue'), while still producing a feature benefit for 'circle' compared to 'square' or 'shape' (see Figure 1b). Applied to distractor interference, this would leave some room for improvement with intra-dimensional distractors (i.e., distractors defined in the same dimension as the target), which is less compared to the room with cross-dimensional distractors (distractors defined in a different dimension to the target; see also Treisman, 1988). In summary, according to hierarchical feature weighting, if target and distractor are defined in the same dimension, interference cannot be as effectively prevented as when they are defined in different dimensions; by contrast, independent feature weighting should lead to comparable interference reduction with both intra- and cross-dimensional distractors.

Even though top-down control in feature mode has mostly been assumed to be based on independent feature weighting or feature selection, Kumada (1999) casted doubt on this possibility in a re-evaluation of the original search mode experiments: Bacon and Egeth (1994) had attempted to discourage observers from using a singleton mode by adding other unique shapes, in addition to the target shape, to the search displays. In one third of the trials, the target was either the only unique shape, one of two unique shapes, or one of three unique shapes. While the presentation of a color distractor (in addition to the shape singletons) caused no significant interference, as expected if observers were operating in feature mode, RTs became significantly affected by the number of unique shapes. While Bacon and Egeth attributed the slowed RTs with additional unique shapes to reduced nontarget-nontarget similarity (Duncan & Humphreys, 1989), Kumada pointed out that they might as well reflect attentional capture by (one of) the additional shape singletons. In support of this argument, Kumada (similar to van Zoest & Donk, 2004) reported that with target and distractor defined in the same dimension, even distractors less salient than the target caused interference.

It should be noted, though, that Kumada (1999) did not control whether his participants were indeed using a feature mode as opposed to a singleton mode. At variance with Kumada's findings, there are several reports of interference prevention, or at least reduction, with target and distractor defined in the same dimension (when controlling for the implementation of a feature mode). However, all these studies used either a temporal search task involving rapid serial visual presentation (RSVP; e.g., Folk, Leber, & Egeth, 2002; Leber & Egeth, 2006a; Leber et al., 2009), or a spatial-cueing procedure with temporally separated cue and target displays (e.g., Folk & Remington, 1998; Lamy, Leber, & Egeth, 2004; Eimer, Kiss, Press, & Sauter, 2009). That is, quite unlike the standard visual search paradigm, target and distractor were not presented simultaneously in these studies. Given this, it is unclear whether their results generalize to visual search. Consequently, the third issue to be examined concerns the specificity of top-down control in reducing or preventing interference by distractors, that is: Are feature mode observers really capable of operating highly specific top-down control (i.e., able to completely prevent interference by intra-dimensional distractors), or does hierarchical feature weighting offer a better explanation?

Purpose of the present study and overview of the experiments

The present study was designed to clarify the three open issues elaborated above, by examining interference effects in different induced search modes under various practice conditions and with both intra- and cross-dimensional distractors. It is important to point out that in situations in which the search task can be successfully accomplished using either search mode (for instance, even though the target-defining feature is known exactly, making a feature search possible, the target may also be easily detectable using a salience-based strategy), it is not possible to induce a feature mode simply by instructing observers to use one (Kawahara, 2010). However, it is possible to induce a feature mode by making observers use it in an appropriately designed training task, as has been demonstrated in several studies (Leber and Egeth, 2006a, 2006b; Leber et al., 2009). Therefore, the present study applied the training paradigm of Leber and Egeth (2006b), so as to ensure that observers were indeed using the intended search strategies.

Leber and Egeth (2006b) initially trained two separate groups of participants to use either a singleton or a feature mode. This training phase with separate tasks was followed by a test phase in which the task was identical for the two groups and, importantly, permitted the observers to use either search mode. It was observed that in the latter task, the singleton mode observers exhibited significant distractor interference, whereas the feature mode observers showed no sign of a capture effect at all. It was concluded that both groups stuck to the respective search mode they were induced to use during the initial training phase.

The present Experiment 1 was designed to replicate Leber and Egeth's (2006b) results of divergent interference patterns in singleton and feature mode, while also examining for interference reduction effects as a function of distractor practice, for both groups of observers. Experiment 2 tested whether the results of Leber and Egeth (2006b) could also be replicated without distractor practice; that is, without observers being presented with distractors during the respective training phases. The subsequent Experiments 3, 4, and 5 were designed to explore the specificity of top-down control: The test phase of Experiment 3 introduced intra-dimensional distractors. Experiments 4 and 5 both presented cross-dimensional distractors in the training and test phases, however with the distractor-defining feature (in the respective distractor dimension) changing between the two experimental phases. If interference reduction between the two phases operated based on hierarchical feature weighing, as predicted by the dimension-weighting account, then training with a distractor defined in the same dimension, albeit by a different feature, as the test phase distractor should nevertheless be conducive to minimizing interference in the test phase.

EXPERIMENT 1

Experiment 1 was a replication of Leber and Egeth's (2006b) study and, thus, closely modeled after their methodology. Two groups of participants were trained to use either a singleton or a feature mode. Observers in the singleton mode training searched for a consistently shape-defined but featurally non-predictable target among shape-homogeneous nontargets. As the observers did not know the exact target-defining feature on a given trial, they had no other choice but to adopt a singleton mode, that is, to search for any discontinuity in the display. Observers in the feature mode training searched for a target of consistent shape among shape-heterogeneous nontargets (similar to Bacon & Egeth, 1994). By adding additional unique shapes to the display, a stimulus-driven search strategy was rendered ineffective and observers were forced to adopt a feature mode. The two different training phases were followed by an identical test phase, of so-called *option trials* (e.g., Leber & Egeth, 2006a), for both search groups: on these trials, the target was consistent (i.e., always the same) in shape and the nontargets were homogeneous – thus, it was possible to operate in either search mode for finding the target. In this situation, where both search modes are available in principle, observers typically maintain their previously established search mode (see Leber & Egeth, 2006a, 2006b; Leber et al., 2009). In both the training and test phases, a color distractor was presented in half of the trials (the other half were no-distractor trials). Additionally, the number of items in the search display (the 'display size') was manipulated to permit search efficiency (i.e., the slope of the function relating search RT to display size) to be assessed. Controlling search efficiency is necessary to circumvent the 'serial-search criticism' of Theeuwes (2004), who had suggested that attentional capture occurs only in efficient, but not inefficient, search. The purpose of Experiment 1 was to replicate Leber and Egeth's (2006b) finding of divergent interference patterns in different search modes, while also testing for interference reduction through practice over the course of the experiment.

Method

Participants. Twenty-eight (17 female, all right-handed) observers with a median-age of 21 years were recruited for this experiment (from the subject panel of the Chair of General and Experimental Psychology, Ludwig Maximilian University of Munich). They were randomly assigned to one of the two training groups: half of them to the singleton mode group, the other half to the feature mode group. All reported normal or corrected-to-normal visual acuity and color vision. They were either paid for their participation (at a rate of 8 Euros per hour, approximately 11 USD) or received a course credit.

Apparatus. The experiment was conducted in a sound-isolated, dimly-lit chamber with black interior. Stimuli were generated with a ViSaGe system (Cambridge Research Ltd., UK), controlled by a personal computer running under the Windows XP operating system, and presented on a 22-inch Mitsubishi Diamond Pro 2070SB with a screen refresh rate of 120 Hz and a screen resolution of 1104 x 828 pixels. Observers viewed the monitor from a distance of about 70 cm, maintained by using a chin rest. They reported the horizontal or vertical orientation of a line within the target item by pressing the right or left button of a mouse using their left- or, respectively, right-hand index finger.

Stimuli. The stimulus display, presented on a black background, consisted of either five or nine outline shapes whose geometric centers were equidistantly arranged on the circumference of an imaginary circle with a radius of 3.75° of visual angle around a white fixation cross. This fixation cross (0.5° wide x 0.5° high; line width of 0.05°) was situated in the center of the screen. The outline shapes presented were a circle (diameter of 1.5°), a square (side length of 1.3°), a diamond (a square rotated through 45°), and an equilateral upwards-pointing triangle (side length of 1.3°). All contours had a line width of 0.1° and were green (RGB: 0.36, 0.97, 0.42). If a distractor was present, one of the shapes was red (RGB: 1, 0, 0). Centered inside all of the shapes, there was a white line (length of 0.5°; width of 0.05°) which could be either vertical or horizontal in orientation.

Design. There were two different training phases, following which both training groups participated in an identical test phase. In the feature mode training the target item was always a circle and thus consistent in shape. The nontargets were heterogeneous in shape and comprised always a diamond and a triangle, while the remaining nontarget items were squares. In the singleton mode training the target item varied in shape and could either be a circle, a diamond, or a triangle. Each of these target shapes was presented randomly on one third of the trials. The nontargets in this training phase were always squares and therefore homogeneous in shape. During the test phase, all observers constantly searched for a circle among homogeneous squares. Spatial positioning of the items was randomized in all trials.

During both training phases and the test phase, half of the search displays contained five items and half nine items. In half of the trials, there was a color distractor present: on these trials, one of the nontarget items was red. The line orientation inside the target shape was vertical on half of the trials and horizontal on the other half. The orientations of the lines inside the nontarget shapes were random and independent of each other. Figure 2 shows examples of the displays used during the training and test phases.

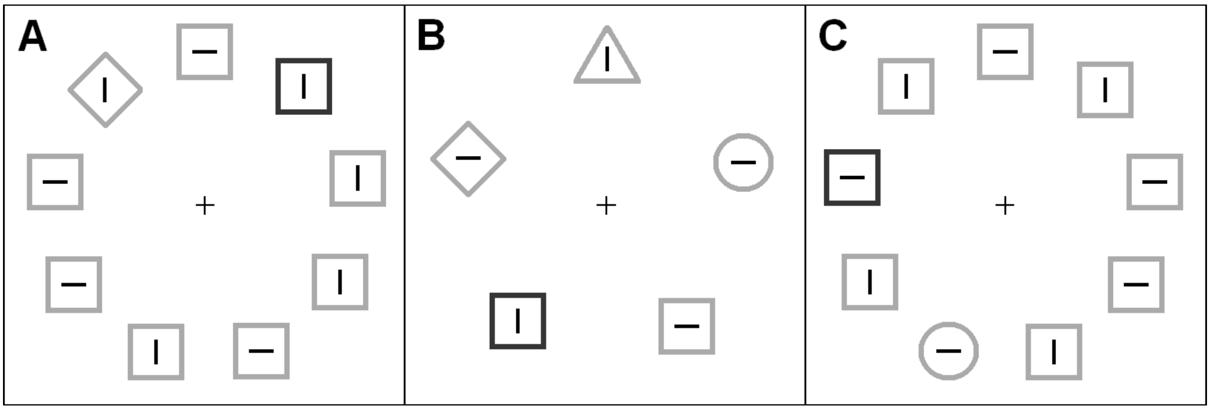

Figure 2. Illustration of stimulus displays used in the two training phases and the test phase of Experiment 1. Light-grey items were green, dark-grey items red. In half of the trials, a color-defined distractor was present. (A) In the singleton mode training phase, the target was randomly a diamond, a circle, or a triangle. (B) In the feature training phase, the target was always a circle; on every trial, two additional unique shapes were present: a diamond and a triangle. (C) In the test phase, the target was always a circle; no other unique forms were present.

Combination of the factors display size, distractor condition, and line orientation resulted in eight different conditions which were repeated 60 times both during training and test. Hence, there were 480 trials per phase, which were presented in eight blocks of 60 trials. Presentation order of the trials was randomized per phase. The training phase was preceded by a practice block with 24 trials, which was not included in the analysis.

Procedure. Prior to the experiment, all observers received both written and oral instructions: The observers in the singleton mode training were asked to search for the item with the unique shape; the observers in the feature mode training were asked to search for the circle. In the test phase, both groups were instructed to search for the circle. Half of the observers had to press the right mouse button if the line inside the target item was vertical and the left mouse button if the line was horizontal. For the other half, this assignment was reversed. All participants were told to proceed as fast and accurately as possible.

Each trial started with the presentation of the fixation cross for a random duration ranging from 500 ms to 1500 ms. Thereupon the whole search display appeared and remained visible until the observer reacted. If the response was correct, the fixation cross reappeared and a new trial begun. If the response was incorrect, the word 'Fehler' (German for error) was presented in capital letters in the center of the screen for 1500 ms before a new trial started. At the end of each block of trials, observers were informed about their percentage error rate in the previous block via a message on the screen. The next block started upon a button press by the observer. The whole session lasted approximately 45 minutes.

Results

For both the training and the test phase, RTs below 200 ms and more than 3 standard deviations above an observer's mean per display size and distractor condition were discarded as outliers (1.80% of all trials). Response error trials were excluded as well (4.04% of all trials). Table 1 gives an overview of the error rates under the different experimental conditions. Neither the error rates in the training phase nor those in the test phase were systematically related to group assignment, display size, or distractor condition (all $ps > .12$).

Table 1

Mean error rates [%] for all experiments (E1–E5), separately for the two search groups, dependent on display size and distractor presence

	Feature mode group				Singleton mode group			
	Display size 5		Display size 9		Display size 5		Display size 9	
distractor	absent	present	absent	present	absent	present	absent	Present
E1 training	3.82	3.68	3.65	3.74	6.58	5.64	5.17	6.01
E1 test	2.12	2.60	3.26	2.90	3.70	3.77	3.75	3.96
E2 training	4.34	-	4.02	-	5.44	-	4.53	-
E2 test	2.30	3.08	3.78	3.39	3.27	2.67	3.28	3.98
E3 training	3.25	2.98	4.60	3.10	6.18	7.63	6.37	6.82
E3 test	2.75	3.04	2.76	2.56	3.11	4.94	4.53	4.09
E4 training	4.44	2.78	4.08	4.23	3.81	4.23	3.40	4.24
E4 test	3.80	3.63	3.08	2.79	2.93	3.32	2.39	4.26
E5 training	3.34	3.61	3.51	4.72	4.40	4.26	4.09	4.92
E5 test	3.44	3.82	3.00	3.74	3.39	4.60	3.15	4.74

The RTs of the *training phase* were entered into a mixed-design ANOVA with training (feature or singleton mode) as a between-subjects factor and display size (5 or 9 items) and distractor condition (present or absent) as within-subjects factors. For reasons of clarity and the sake of brevity, the presentation and discussion of the results will focus on the main and interaction RT effects concerning distractor interference, for the current and the subsequent experiments. Mean RTs as well as search slopes for both search groups can be seen in Table 2. Additionally, the results of (near) significant main and interaction effects not related to distractor interference are summarized in Table 3. Main and interaction effects that are not reported were not significant. Overall, the distractor was able to capture attention, as indicated by a significant main effect of distractor condition, F (1, 26) = 95.25, p < .001, MSE = 772.96, η^2_p = .79. However, this main effect was qualified by a significant distractor condition x training interaction, F (1, 26) = 62.46, p < .001, MSE = 772.96, η^2_p = .71. Planned comparisons revealed significant interference in both the feature mode (9.82 ms; t (13) = -2.17, p < .05) and the singleton mode group (93.09 ms; t (13) = -9.70, p < .001) – however, with this effect being much more marked in the latter group (see Figure 3).

Table 2

Mean RTs [ms] (standard deviation in brackets) and search slopes [ms/item] for all experiments (E1–E5), separately for the two search groups

	Feature mode group		Singleton mode group	
	RT [ms] (SD)	Slope [ms/item]	RT [ms] (SD)	Slope [ms/item]
E1 training	660.30 (99.13)	6.34	946.79 (154.42)	-2.78
E1 test	583.63 (63.46)	-0.05	636.00 (89.89)	-3.25
E2 training	663.61 (124.01)	1.89	847.19 (179.02)	-12.69
E2 test	623.48 (115.93)	-0.39	664.30 (90.37)	-2.92
E3 training	687.05 (98.35)	3.30	773.48 (120.16)	-9.46
E3 test	638.35 (97.77)	-2.51	616.63 (51.25)	-2.23
E4 training	664.06 (88.15)	5.32	760.20 (175.50)	-6.46
E4 test	613.60 (78.54)	1.21	601.84 (89.74)	-1.65

E5 training	630.77 (106.05)	7.74	723.46 (128.95)	4.07
E5 test	612.54 (95.84)	4.49	606.37 (79.51)	3.68

Table 3

Additional significant or near-significant ANOVA effects for Experiments 1–5: The main effect of group assignment was significant or near-significant in all training phases, reflecting slower RTs for the singleton mode group compared to the feature mode group (see Table 2 for descriptive results). Similarly, the interaction group assignment x display size was significant in all training phases, reflecting more positive search slopes for the feature mode compared to the singleton mode group (again, see Table 2). In the test phase of E3 and in both the training and test phases of E5, there was also a significant main effect of display size, reflecting an overall tendency to negative search slopes in E3 and to positive slopes in E5.

	ANOVA	MSE	η^2_p
E1 training: main effect group	$F\,(1, 26) = 34.12$, $p < .001$ *	67,326.90	.57
E1 training: group x diplay size	$F\,(1, 26) = 8.49$, $p < .01$ *	1,078.07	.25
E1 test: main effect group	$F\,(1, 26) = 3.18$, $p = .09$, n.s.	24,192.18	.11
E1 test: main effect display size	$F\,(1, 26) = 4.11$, $p = .053$, n.s.	298.99	.14
E1 test: group x diplay size	$F\,(1, 26) = 3.90$, $p = .059$, n.s.	298.99	.13
E2 training: main effect group	$F\,(1, 14) = 5.69$, $p < .05$ *	47,438.11	.29
E2 training: main effect display size	$F\,(1, 14) = 3.33$, $p = .09$, n.s.	1,120.32	.19
E2 training: group x diplay size	$F\,(1, 14) = 6.07$, $p < .05$ *	1,120.32	.30
E3 training: main effect group	$F\,(1, 22) = 3.73$, $p = .07$, n.s.	48,351.00	.15
E3 training: group x display size	$F\,(1, 22) = 10.26$, $p < .01$ *	1,564.47	.32
E3 test: main effect display size	$F\,(1, 22) = 4.60$, $p < .05$ *	486.95	.17
E4 training: main effect group	$F\,(1, 20) = 2.65$, $p = .12$, n.s.	76,917.30	.12
E4 training: group x display size	$F\,(1, 20) = 15.35$, $p < .01$ *	794.89	.43
E5 training: main effect group	$F\,(1, 15) = 26.35$, $p < .001$ *	10,420.72	.64
E5 training: main effect display size	$F\,(1, 15) = 37.37$, $p < .001$ *	473.61	.71
E5 training: group x display size	$F\,(1, 15) = 10.42$, $p < .01$ *	162.68	.41
E5 test: main effect display size	$F\,(1, 15) = 28.89$, $p < .001$ *	294.99	.66

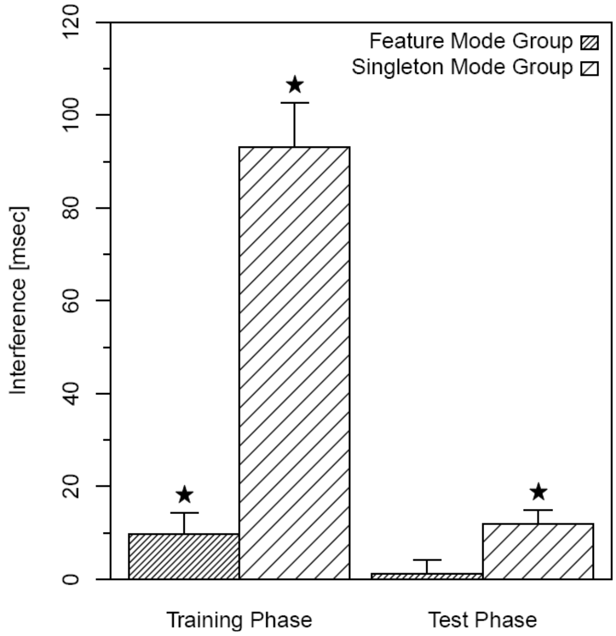

Figure 3. Experiment 1: Mean interference caused by the color-distractor, for the two search groups and the two experimental phases. Significant interference effects (i.e., significantly slower RTs for distractor-present vs. distractor-absent trials) are marked by an asterisk. Error bars denote one standard error of the mean interference.

To examine the time course of interference in both search groups, the experimental session was split into four trial bins of 240 trials each, such that there were two trial bins for the training phase and two for the test phase. Table 4 shows the interference for both search groups calculated separately for all trial intervals. The interference values were analyzed by a mixed 2 (training) x 4 (epoch of experiment) ANOVA. There was a significant main effect of training, F (1, 26) = 65.00, p < .001, MSE = 991.91, η^2_p = .71, reflecting the overall higher interference in the singleton mode group compared to the feature mode group. Both the main effect epoch of the experiment (F (2.19, 56.98) = 33.35, p < .001, MSE = 928.73, η^2_p = .56, Greenhouse-Geisser corrected-values) and the interaction training x epoch of experiment (F (2.19, 56.98) = 26.16, p < 001, MSE = 928.73, η^2_p = .50, Greenhouse-Geisser-corrected values) were significant. To disentangle these effects, Bonferroni-corrected post-hoc tests were conducted on the interference scores of both search groups. While the feature mode group could not significantly reduce the interference over the course of the experiment, the singleton mode group showed a clear pattern of interference reduction: interference was significantly larger in the first half of the training phase compared to the second half, t (13) = 4.72, p < .01. In line with this, this group could further reduce interference from the second half of the training phase to the first half of the test phase, t (13) = 5.42, p < .001. Beyond this, the singleton mode group showed no further reliable reduction from the first to the second half of the test phase, t (13) = 0.34, *ns*.

Table 4

Mean interference [ms] caused by the color distractor over the course of Experiment 1, for the two search groups

	Training phase		Test phase	
	Trial 1-240	Trial 241-480	Trial 481-720	Trial 721-960
Feature mode group	6.03	14.38	0.90	1.17
Singleton mode group	123.71	66.56	13.09	11.07

To rule out that this pattern of results was due to a general speeding-up of RTs (with practice) reducing the interference effects, we also examined a relative measure of interference, namely, the percentage RT slowing on distractor-present trials relative to baseline performance (RTs on distractor-absent trials). Carrying out the time course analysis described above on this relative measure yielded essentially the same pattern of results.

Discussion

The results of Experiment 1 essentially replicate Leber and Egeth's (2006b) findings: In the test phase, only the singleton mode group, but not the feature mode group, showed significant interference – which indicates that when confronted with option trials, both search groups persisted with their once-established search mode. Note, though, that for the training phases, the results are somewhat different from the findings of Leber and Egeth (2006b): while they reported only minor, non-significant interference in the feature mode group, the interference for the feature mode group in the present training phase, albeit small, was significant. This is difficult to reconcile with an architectural interpretation of the feature mode, according to which top-down attentional selection is based directly on the relevant feature map (see Figure 1a): if this were the case, there should never be any interference by items not sharing the target-defining feature at all in this search mode.

Over the course of the experiment, the singleton mode group exhibited a very substantial decrease in interference: If observers in this group had operated in a purely stimulus-driven search mode (solely reliant on stimulus salience, as suggested by the search-mode account), interference reduction should not have occurred as the physical salience of the distractor remained constant throughout the experiment. The fact that the singleton mode group showed a clear, gradual reduction in interference (see Table 4) is more in line with observers acquiring an effective suppression strategy through distractor practice. Most importantly, this group even showed a significant interference reduction from the first to the second half of the training phase, during which the target feature was unpredictable and observers were therefore unable to switch to a feature mode. With regard to the further interference reduction from the second half of the singleton mode training phase to the first half of the test phase, the present data do not allow us to disentangle effects of practice from those arising from differences in mixed- versus fixed-singleton search.[4]

Note that also Leber and Egeth (2006b) already acknowledged an interference reduction over the course of the singleton mode training, which they briefly discussed as a gradual performance improvement. However, to be able to account for interference reduction effects in this search mode (especially in the training phases, where target feature information is consistently unavailable), one needs to assume an additional mechanism mediating such a reduction. This is because, as outlined above, if the singleton mode were rigidly based on stimulus salience, no reduction would be possible with the distractor being the most salient item in the display. Based on the present results, distractor practice might be suggested as a possible mechanism that brings about interference reduction even in singleton mode.

However, if practice were indeed critical for achieving interference reduction, one would have also expected a gradual interference decrease in feature mode – but this was not observed. Nevertheless, it remains possible that interference reduction did also occur in this group, but more rapidly than would be discernible by the analysis (based on comparing successive ‘bins’ of 240 trials) conducted here: It is possible that in the present experiment interference reduction in feature mode occurred already during the initial practice block, which preceded the training phase. These trials could, however, not be reasonably analyzed as the observers had been specifically told that the practice trials would not be recorded for analysis and they were therefore free to take their time to familiarize with the task.

Given this, we conducted an additional experiment with a group of 16 new observers, who were presented with six blocks of feature mode trials (48 trials per block) identical to those

[4] It has been pointed out (e.g., Lamy et al., 2006; Lamy & Yashar, 2008) that mixed-singleton search (as in the singleton mode training) differs from fixed-singleton search (as in the test phase) in several aspects: In mixed- compared to fixed-singleton search, one usually finds slower RTs, negative rather than flat search slopes, and greater distractor interference. However, in studies reporting higher distractor interference in mixed- compared to fixed-singleton search, target and nontarget feature values usually switched during mixed-singleton search (e.g., Lamy et al., 2006; Lamy & Yashar, 2008). In contrast, in our singleton mode training, only the target feature changed, while the nontarget feature stayed constant. Pinto, Olivers, and Theeuwes (2005, Experiment 2) used a comparable condition and found only a non-significant trend towards greater interference in the mixed- compared to the fixed-singleton search condition. Nevertheless, we acknowledge the possibility that the interference reduction shown by the singleton mode group from the second half of the training phase to the first half of the test phase was partly owing to differences in mixed- compared to fixed-singleton search.

in Experiment 1. No distractors were shown during the first two blocks, thus permitting the participants to familiarize themselves with the task without at the same time gaining distractor practice. In the subsequent four blocks, color distractors were shown. An analysis of the interference in the latter four blocks revealed significant interference only during the first block (45.69 ms; t (15) = -2.13, p < .05, one-tailed), while interference was non-significant and close to zero in the subsequent blocks of trials (block 2: -2.40 ms; block 3: -3.20 ms; block 4: 0.37 ms). Consequently, also for observers in feature mode, distractor practice seems to be essential for interference reduction – although this reduction seems to occur markedly faster compared to singleton mode.

EXPERIMENT 2

Experiment 2 was designed to examine the role of distractor practice for the test phase results reported by Leber and Egeth (2006b) and replicated in the present Experiment 1: Is encountering distractors during the training phases necessary for the search groups to show divergent interference patterns during the test phase? Although Leber and Egeth (2006b) do not state why they presented distractors during their training phases, on their rationale of search mode induction, the presence of distractors during training should not be important: singleton mode observers are assumed to adopt their search mode during training because they are confronted with unpredictably changing target stimuli, preventing them to operate a feature-based search strategy. In contrast, feature mode observers are assumed to engage in their search mode during training because their search displays contain heterogeneous items, rendering a salience-based search strategy error-prone. Hence, if the application of a feature mode is the causal mechanism underlying interference reduction, both search groups should show test phase behavior similar to that in Experiment 1. By contrast, if there is a relevant contribution of distractor practice, overall test phase interference should be larger in Experiment 2 compared to Experiment 1, for both search groups. To test these differential predictions, the design of Experiment 2 was identical to that of Experiment 1, except that no distractors were shown during the training phases.

Method

With respect to the method, Experiment 2 was comparable to Experiment 1, except for the following differences.

Participants. Sixteen new observers (10 female, all right-handed) with a median age of 25 years and normal or corrected-to-normal visual acuity as well as color vision participated in the second experiment. Again half of the observers were randomly assigned to the singleton mode group and half to the feature mode group.

Design. There were no distractors shown during the training phases of this experiment. Hence, only the factors display size (5 vs. 9) and line orientation (vertical vs. horizontal) were varied independently, resulting in four unique (combinatorial) conditions which were repeated 120 times during the training phase. These 480 trials were presented in eight blocks of 60 trials each, with presentation order randomized per block, so that each condition was repeated 15 times per block. There were no practice trials preceding the training phase. The test phase was identical to that in Experiment 1, except that each of the 8 blocks consisted of 64 trials, resulting in 512 test phase trials. Within a block, each of the 8 factor combinations (display size x distractor condition x line orientation) was repeated 8 times in random order.

Results

For both experimental phases, RTs faster than 200 ms or more than 3 standard deviations above the individual observer's mean per condition were discarded as outliers (overall, 1.82% of trials). In addition, error trials were excluded from the analysis (3.97% of all trials). Separate ANOVAs on training and test error rates did not reveal any significant effects (all *p*s $>$ .05); mean error rates for the different conditions are summarized in Table 1.

The *training phase* RTs were analyzed using a mixed-design ANOVA with training phase as a between-subjects factor and display size as a within-subjects factor. Tables 2 and 3 provide an overview of the results.

The *test phase* of Experiment 2 was identical to that of Experiment 1. Analogously to the analysis conducted for Experiment 1, the *test phase* RTs of Experiment 2 were entered into a 2 (training) x 2 (display size) x 2 (distractor condition) mixed ANOVA. As in Experiment 1, there was a significant main effect of distractor condition, F (1, 14) = 38.48, p < .001, MSE = 649.55, η^2_p = .73. However, unlike in Experiment 1, distractor condition did not significantly interact with training, F (1, 14) < 1, p = .73, MSE = 649.55, η^2_p = .01. As can be seen from Figure 4, both search groups showed very similar interference: The singleton mode group (41.83 ms; t (7) = -4.48, p < .01) as well as the feature mode group (37.25 ms; t (7) = -4.31, p < .01) were significantly slowed by the color distractor in the test phase of Experiment 2. Numerically, the overall interference effects for both groups were considerably larger in the test phase of Experiment 2 compared to that of Experiment 1. To statistically examine this observation, the interference effects were compared between both experiments, using Welch's t-tests for unequal variances (Levene's test had shown that equal variances could not be assumed): compared to the respective search groups of Experiment 1, both the singleton mode group (t (8.51) = -3.05, $p < .05$) and the feature mode group (t (8.68) = -3.95, $p < .01$) of Experiment 2 showed significantly increased interference.

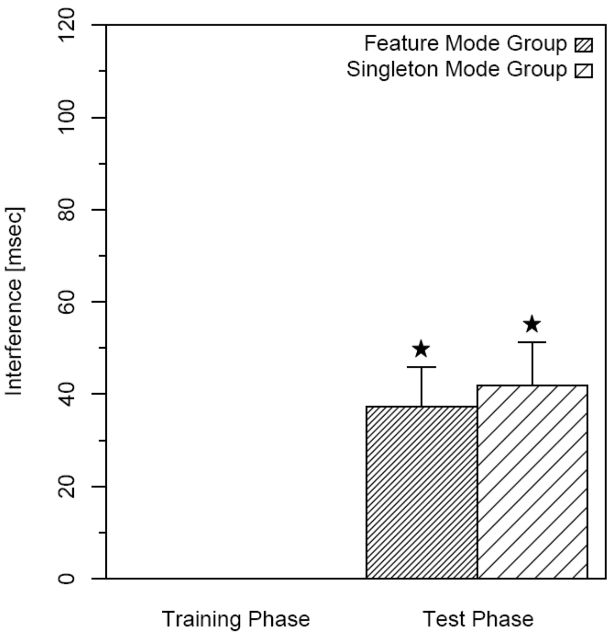

Figure 4. Experiment 2: Mean interference caused by the color distractor, for the two search groups. As no distractors were shown during the training phase, there could not logically be interference in this condition (so the plot is empty). Significant interference effects are marked by an asterisk. Error bars denote one standard error of the mean interference.

Discussion

In the test phase of Experiment 2, feature mode observers, too (i.e., as well as singleton mode observers), were distracted significantly by a color distractor that they had not encountered beforehand. If the mere operation of a feature mode were responsible for interference reduction, this group should have been able to avoid interference even without distractor practice in the training phase – which was not the case. Instead, the finding of comparable interference effects between both groups suggests that distractor training is a prerequisite for effective interference reduction. In addition, the present data show that interference reduction is not a binary, all-or-nothing, process, with complete elimination of interference in feature mode and no reduction in singleton mode: without prior distractor practice, feature mode observers (in Experiment 2) were not able to prevent attentional capture by the color distractor; and for both search groups, the test phase interference varied significantly depending on the presence (Experiment 1) versus the absence (Experiment 2) of distractors during the preceding training phases. This adds further support to the notion that interference reduction is possible even when observers are operating in singleton mode, as was already suggested by Experiment 1.

Note that, in contrast to the present Experiment 2, all studies that have reported carry-over of search mode from training to option trials (Leber and Egeth, 2006a, 2006b; Leber et al., 2009), as evidenced by differential interference effects in option blocks, did involve the presentation of distractors during the training phases. This suggests that for these studies, too, distractor presence during training was a critical factor for their finding of the differential interference effects in option blocks.

EXPERIMENT 3

Experiments 3–5 were designed to investigate the specificity of top-down control. Experiment 3, in particular, was designed to examine whether observers using a feature mode can prevent or modulate interference by distractors defined in the same dimension as the target, that is: when training with ‘circle’ defining the shape target, can star-shaped distractors be effectively ignored in the test phase? To this end, the two search mode induction phases were followed by an identical test phase for both groups of participants, during which intra-dimensional distractors were presented. If top-down control in feature mode were based on selection from the relevant feature map or on independent feature weighting (see Figure 1a), feature mode observers should be able to prevent or at least reduce interference by a distractor defined by an irrelevant feature within the target dimension. By contrast, if feature weighting were hierarchically organized, the weighting of the target feature would bring along an increased weighting of the intra-dimensional distractor. Accordingly, feature mode observers should not be able to completely prevent interference by this distractor and both search groups should exhibit substantial interference.

As Experiment 2 had demonstrated the critical role of distractor practice for interference reduction, distractors were already presented during the training phases of Experiments 3–5. While intra-dimensional distractors were presented during the test phase of Experiment 3, the logic underlying singleton mode induction made it impossible to present the same distractors during the training phases: one cannot logically instruct observers to search for a ‘unique’ shape item if another singleton shape item, in addition to the target, is present in half the trials. Therefore, cross-dimensional color distractors (like those in Experiment 1) were presented during both training phases of Experiment 3.

Previous research had shown that search modes are also carried over from training to test if different target and distractor feature sets are used during the training and test phases (Leber et al., 2009).

Method

Regarding the methodological details, Experiment 3 was identical to Experiment 1 with the following exceptions.

Participants. Twenty-four observers (21 female, 22 right-handed) with a median age of 21 years and normal or corrected-to-normal visual acuity as well as color vision participated in this experiment. Half of the observers were randomly assigned to the singleton mode group, and half to the feature mode group.

Stimuli. The stimulus material was identical to that in Experiment 1, with one exception: during the test phase of Experiment 3, a form-defined, instead of a color-defined, distractor was presented. In the distractor-present condition, one of the squares was replaced by an equilateral pentagonal star (side length of 0.7°).

Results

For both phases, RTs below 200 ms and more than 3 standard deviations above an observer's mean per display size and distractor condition were discarded as outliers (1.88% of all trials). Furthermore, error trials were excluded from the analysis (4.34% of all trials). A mixed-design ANOVA of the training phase error rates revealed a significant main effect of training, F (1, 22) = 4.38, $p < .05$, MSE = 58.51, $\eta^2_p = .17$: singleton mode observers (M = 6.75%; SD = 4.86) made significantly more errors than feature mode observers (M = 3.49%; SD = 2.39). As this effect did not go against the trend of the RTs, a speed-accuracy trade-off can be ruled out. No other main or interaction effects were significant (all ps > .10). The same mixed-design ANOVA did not reveal any significant effects of the test phase on the error rates (all ps > .10). See Table 1 for a summary of the mean error rates.

The results of the two *training phases*, during which color distractors were shown, were examined in a 2 (training) x 2 (display size) x 2 (distractor condition) mixed ANOVA (see Table 2 and Table 3 for results unrelated to distractor interference). The training phase of Experiment 3 was identical to that of Experiment 1, and exhibited comparable results: The main effect of distractor condition was significant, F (1, 22) = 28.68, $p < .001$, MSE = 762.39, $\eta^2_p = .57$, and qualified by a significant distractor condition x training interaction, F (1, 22) = 24.59, $p < .001$, MSE = 762.39, $\eta^2_p = .53$: As can be seen in Figure 5, the singleton mode group exhibited significant interference (57.85 ms; t (11) = -5.67, p < .001), while the feature mode group did not (2.26 ms; t (11) = -0.48, *ns*).

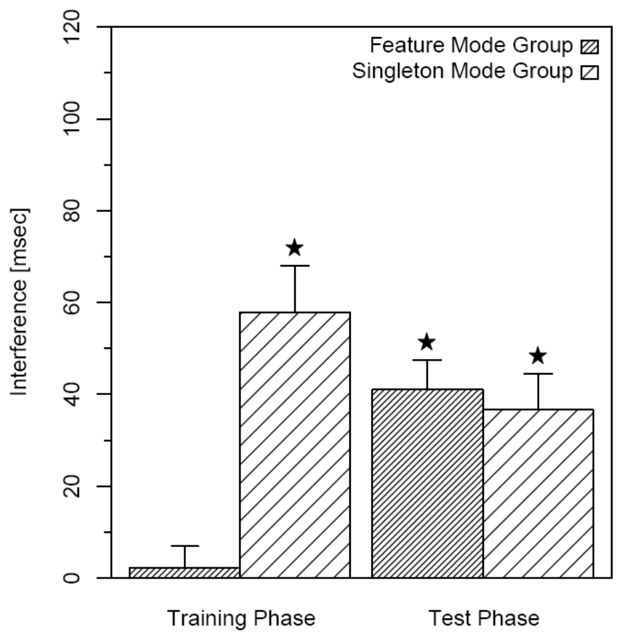

Figure 5. Experiment 3: Mean interference caused by the color-distractor in the training phase and by the shape-distractor in the test phase, for the two search groups. Significant interference effects are marked by an asterisk. Error bars denote one standard error of the mean interference.

The RTs of the *test phase*, in which an intra-dimensional distractor was introduced, were analyzed in the same manner. The ANOVA revealed a significant main effect of distractor condition, F (1, 22) = 57.36, p < .001, MSE = 631.62, η^2_p = .72, which did not interact with training, F (1, 22) < 1, p = .68, MSE = 631.62, η^2_p = .01: As can be seen in Figure 5, the intra-dimensional distractor caused significant and numerically similar interference for both the singleton mode group (36.63 ms; t (11) = -4.67, p < .001) and the feature mode group (40.99 ms; t (11) = -6.24, p < .001).

Discussion

In the test phase of Experiment 3, the presentation of a distractor which was defined in the same dimension as the target caused significant interference not only for the singleton mode group, but also for the feature mode group, even though feature mode observers successfully acquired a suppression strategy for distractors defined in a different dimension than the target ('red') in the training phase. The finding that the feature mode group failed to escape interference from an intra-dimensional distractor is at variance with the assumption that top-down control in this search mode is highly specific, that is, can be targeted at a specific feature independently of all other features: had the interference reduction in feature mode during the training phase really been due to selective processing of the target feature only, distractors not sharing the target-defining feature should not have caused interference in the test phase – whatever the distractor dimension. Note that this pattern of results is in principle consistent with Experiment 3 of Bacon and Egeth (1994), in which they induced a feature mode for a shape-defined target by adding additional unique shapes to their search displays. They found RTs to be slowed with more unique shapes, while RTs were unaffected by the presence of a color singleton. Thus, while feature mode observers are able to effectively shield themselves against interference from distractors defined in an irrelevant dimension, they are unable to do so for intra-dimensional distractors.

Previous evidence in favor of a high specificity of top-down control in preventing distractor interference in feature mode has come exclusively from studies using variants of temporal search tasks (e.g., Folk & Remington, 1998; Folk et al., 2002; Lamy et al., 2004; Leber & Egeth, 2006a; Leber et al., 2009), as opposed to spatial search. Based on the results of Experiment 3, one has to conclude that the findings, and implications, of temporal search studies do not readily extend to standard spatial visual search situations in which target and distractor are presented simultaneously. While previous visual search studies that have found attentional capture by intra-dimensional distractors (e.g., Kumada, 1999; van Zoest & Donk, 2004) may have been vulnerable to the criticism that both search modes were available to the observers and, hence, that they operated a singleton mode, Experiment 3 used a training paradigm to assure observers were indeed operating in feature mode.[5]

EXPERIMENT 4

Experiment 3 had shown that top-down interference reduction in feature mode is not sufficiently specific to prevent intra-dimensional distractors from affecting search performance. Experiment 4 was designed to more positively test the suggested alternative hypothesis that top-down feature weighting is hierarchically organized. To this end, two groups of observers were trained to use either a feature mode or a singleton mode. During both training phases, orange distractors were shown; during the test phase, the distractors were pink. If interference reduction were based on hierarchical feature weighting, both

[5] We acknowledge the possibility that observers in the feature mode group changed their search mode to a singleton mode during the test phase and therefore exhibited significant distractor interference. To explore this possibility, we analyzed the first block (60 trials) of the test phase: if the observers in the feature mode group changed to a singleton mode over the course of the test phase, they should at least show less distractor interference compared to the singleton mode group at the beginning of the test phase, when they were still using a feature mode. However, even in the first 60 trials, the feature mode group exhibited significant distractor interference (t (11) = -3.84, p < .01), which did not significantly differ from the distractor interference in the singleton mode group (t (22) = 0.74, *ns*).

groups of observers should acquire a suppression strategy (i.e., down-weighting) for 'orange' during the training phases. This suppression should spread to other features of the distractor dimension (color). Consequently, when confronted with pink distractors in the test phase, the feature mode group should persistently be able to prevent attentional capture despite the change of the distractor-defining feature from training to test. Similarly, the singleton mode group should also be able to utilize the acquired suppression strategy during the test phase and therefore show reduced interference relative to the training phase.

Method

Compared to Experiment 1, only the following changes were made in Experiment 4.

Participants. Twenty-two observers (19 female, all right-handed) with a median age of 25 years and normal or corrected-to-normal visual acuity as well as color vision took part. Half of the observers were randomly assigned to the singleton mode group, and half to the feature mode group.

Stimuli. The stimulus material was identical to that in Experiment 1, except for the distractor colors on distractor-present trials: during training, one of the nontargets was orange (RGB: 0.79, 0.43, 0.07); during test, one of the nontargets was pink (RGB: 0.95, 0, 0.53). The two distractor colors were matched for luminance (orange: 16.8 cd/m², pink: 16.6 cd/m²).

Results

For both the training and test phases, RTs below 200 ms and more than 3 standard deviations above an observer's mean per display size and distractor condition were discarded as outliers (1.94% of all trials). Error trials were discarded as well (3.63% of all trials). Error rates of the training and test phase were analyzed separately using mixed-design ANOVAs (training x display size x distractor condition). These revealed a marginally significant training x distractor condition interaction for the training phase, F (1, 20) = 3.40, p = .08, MSE = 3.11, η^2_p = .15. As can be seen in Table 1, the singleton mode group tended to make slightly more errors if a distractor was present (4.24%) rather than absent (3.61%); this was reversed for the feature mode group, which made fewer errors if a distractor was present (3.51%) rather than absent (4.26%). For the test phase, this training x distractor condition interaction was (also) significant, F (1, 20) = 4.94, p < .05, MSE = 2.04, η^2_p = .20. Again, the singleton mode group made significantly more errors when a distractor was present rather than absent, t (10) = -2.97, p < .05, while there was no significant difference for the feature mode group, t (10) = 0.47, *ns*. As will be described below, this error effect did not go against the RTs of the singleton mode group, ruling out a speed-accuracy trade-off. No other main or interaction effects were significant (all *p*s > .15).

The RTs of the *training phase* of Experiment 4 were examined in a 2 (training) x 2 (display size) x 2 (distractor condition) mixed ANOVA (see also Table 2 and 3). The orange training phase distractor produced a similar result pattern compared to the red training phase distractors presented in Experiments 1 and 3: The ANOVA revealed a significant main effect of distractor condition, F (1, 20) = 14.72, $p < .01$, MSE = 1,580.42, $\eta^2_p = .42$, which was qualified by a significant distractor condition x training interaction, F (1, 20) = 7.44, $p < .05$, MSE = 1,580.42, $\eta^2_p = .27$. As can be seen in Figure 6, the singleton mode group was significantly distracted by the color singleton (55.67 ms; t (10) = -3.72, $p < .01$), while the feature mode group showed no significant distraction effect (9.14 ms; t (10) = -1.18, *ns*).

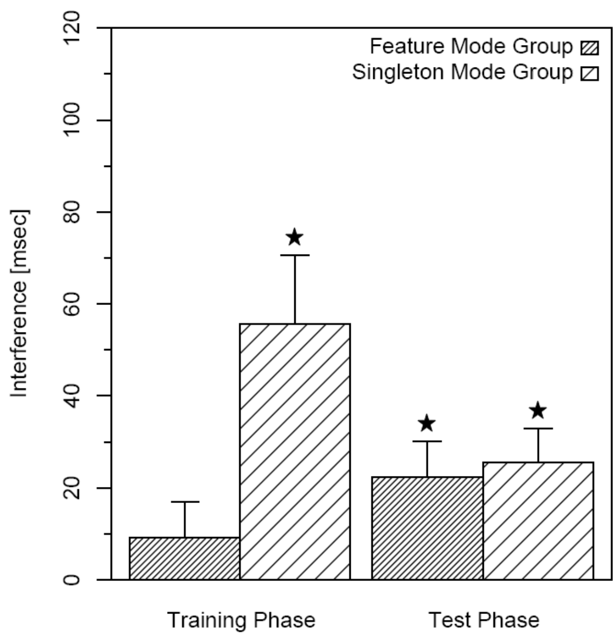

Figure 6. Experiment 4: Mean interference caused by the orange color-distractor in the training phase and by the pink color distractor in the test phase, for the two search groups. Significant interference effects are marked by an asterisk. Error bars denote one standard error of the mean interference.

The RTs of the *test phase*, in which the distractors were pink, were analyzed in the same way. There was a main effect of distractor condition, F (1, 20) = 19.98, $p < .001$, MSE = 629.45, $\eta^2_p = .50$, which did not interact with training, F (1, 20) < 1, $p = .78$, MSE = 629.45, $\eta^2_p = .004$. As can be seen in Figure 6, both the singleton mode group (25.47 ms; t (10) = -3.45, $p < .01$) and the feature mode group (22.36 ms; t (10) = -2.90, $p < .05$) were significantly distracted by the pink distractor. Note, however, that for the singleton mode group, the interference was significantly reduced during the test phase compared to the training phase (25.47 vs. 55.67 ms; t (10) = 2.83, p < .05); by contrast, for the feature mode group, the interference did not significantly differ between the test and training phases (22.36 vs. 9.14 ms; t (10) = -1.73, *ns*).

Discussion

By presenting distractors defined in the same dimension but by different features during the training and test phases of Experiment 4, it was examined whether interference reduction involves hierarchical feature weighting. During the training phases, only the singleton mode group, but not the feature mode group, was significantly distracted by the orange distractor. If the suppression strategy acquired during feature mode training were based on hierarchical feature weighting, this group should have been able to utilize it to effectively prevent attentional capture by the new color distractor introduced in the test phase. However, this was not the case: the feature mode group showed significant attentional capture during the test phase (note, though, that this is qualified by the fact that the capture effect was not reliably increased in the test phase relative to the training phase). The results for the singleton mode group are more in line with hierarchical feature weighting: while this group also showed significant interference during the test phase with the new distractor, the distraction effect was significantly reduced compared to the training phase. However, interference effects in fixed-singleton search, as required in the test phase, may not be directly comparable to interference effects in mixed-singleton search, as required in the singleton mode training (see, e.g., Lamy, Carmel, Egeth, & Leber, 2006; Lamy & Yashar, 2008; see also Footnote 1). Given this, both hierarchical feature weighting and differences between mixed- and fixed-singleton search may have been responsible for the singleton mode group displaying a decrease in interference from training to test. The data obtained in Experiment 4 do not permit us to determine the relative contributions of these two factors.

Thus, in summary, the results of Experiment 4 cannot be interpreted unequivocally in terms of hierarchical feature weighting. However, there is evidence suggesting that hierarchical feature weighting works somewhat differently for the color dimension compared to other dimensions. For instance, Found and Müller (1996; Müller et al., 2003) and Pollmann, Weidner, Müller, and von Cramon (2000) observed ‘feature-specific’ intertrial effects for the color but not for the orientation and, respectively, the motion dimension (note that although the color feature repetition/change effect was significant in these studies, it was still smaller than the color dimension repetition/change effect). To explain this special processing of color stimuli, Found and Müller surmised that the color dimension, unlike other dimensions, might consist of a number of separable ‘sub-dimensions’ representing broad color categories. Consequently, it is conceivable that those color sub-dimensions can be weighted rather independently of each other, therefore allowing top-down control to operate more independently for the color dimension than for other dimensions. If so, then in Experiment 4, it may have been possible that observers learned to effectively suppress distractor signals of one specific color category in the training phase, but less so signals from the distractor color category in the test phase. Consequently, the (in any case equivocal) results of Experiment 4 cannot be taken as an outright rejection of the hypothesis of hierarchical feature weighting. Given this, Experiment 5 was designed to re-examine this hypothesis using another distractor-defining dimension, or domain, namely: orientation/shape (which, on previous evidence, does not fractionate into subdivisions). Note that also the results of Experiment 3, during which interference by an intra-dimensional shape distractor could not be effectively down-regulated, already indicate that feature weighting for the shape dimension might not be independently but rather hierarchically organized.

EXPERIMENT 5

Similar to Experiment 4, Experiment 5 was designed to re-examine the assumption that interference reduction depends on hierarchical feature weighting. However, as discussed above, the different training and test phase distractors in Experiment 5 were not defined in the color dimension as they were in Experiment 4, but in the shape dimension; and conversely, the target was defined in the color dimension.

Observers were trained to use either a feature or a singleton mode. A square-shaped distractor was presented during the training phases and a diamond-shaped distractor during the test phases. If observers in the two search groups were to acquire a suppression strategy for shape distractors in general during their training phases, this should also help them to minimize interference in the test phase, during which they encountered a distractor defined in the same dimension but by a different feature relative to the training phase distractor. Consequently, the feature mode group should persistently be able to prevent attentional capture and the singleton mode group should show comparable or less interference during the test than during the training phase.

Method

Participants. Sixteen (12 female, all right-handed) observers with a median age of 26 years were recruited for this experiment. All of them reported normal or corrected-to-normal visual acuity and color vision.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The stimulus display arrangement was identical to that in Experiment 1. On distractor-absent trials, all stimulus shapes were circles (diameter of 1.5°). On distractor-present trials, one of the nontargets was replaced by a square (side length of 1.3°) during the training phases or by a diamond (a square rotated through 45°) during the test phase. The stimulus shape colors deployed were matched for luminance and included gray (RGB: 0.46, 0.46, 0.46; CIE [Yxy]: 14.6, .28, .32), blue (RGB: 0.40, 0.45, 0.51; CIE [Yxy]: 14.8, .25, .28), red (RGB: 0.54, 0.42, 0.42; CIE [Yxy]: 14.5, .32, .32)) and green (RGB: 0.40, 0.47, 0.40; CIE [Yxy]: 14.5, .28, .36). Instead of being outline shapes, the stimulus shapes were color-filled-in in Experiment 5. The horizontal or vertical line inside all of the shapes was black and had a length of 0.5° (and a line width of 0.1°).

As color was the target-defining dimension and shape the distractor-defining dimension in Experiment 5, we had to use unsaturated color features to reduce the color items' salience, thereby assuring the shape distractors' capturing potential. The relative saliencies of the target and distractor singletons were compared in pre-experimental testing: Observers (N = 10) had to search for singletons defined by the three color features or by the two shape features and indicate the line orientation inside the target item. RTs to the three color singletons did not differ significantly from each other (blue: 744.03 ms, red: 678.87 ms, green: 716.93 ms), nor did RTs to the two shape singletons (square: 591.94 ms, diamond: 601.02 ms), but RTs to the various color singletons were significantly slower than the RTs to both shape singletons (all ps < .01). In addition, all features produced search slopes less than 10 ms/item (blue: -1.45 ms/item, red: 9.26 ms/item, green: 2.35 ms/item, square: 0.26 ms/item, diamond: 4.37 ms/item), indicative of efficient search (Wolfe, 1998). Finally, we conducted an additional pilot experiment to ensure that without prior practice, the diamond distractor presented during the test phase was capable of capturing attention. In the pilot experiment, 10 observers were shown test phase search displays (blue target, diamond distractor) without having completed any training phases beforehand. Under these circumstances, the presence of the diamond distractor generated a significant interference effect of 20.68 ms, t (9) = -3.02, $p < .05$, thus demonstrating its potential to capture attention.

Design and Procedure. Unlike in the previous experiments, group assignment was a within-subjects factor in Experiment 5.[6] The observers participated in two experimental sessions on two consecutive days, conducted at the same time of the day. During each session, the observer completed one of the two training phases and subsequently the test phase. The observers randomly either started with a singleton mode session on day 1 and performed a feature mode session on day 2, or vice versa.

In the feature mode training phase, the target item was always a blue circle and thus consistent in color. The nontargets were heterogeneous in color: on every trial, one nontarget was green and another one red, while the remaining nontargets were gray. The observers were instructed to search for the blue item. In the singleton mode training phase, the target item varied in color and was randomly either blue or red or green. The nontargets in this phase were always gray and thus homogeneous in color. The observers were told to search for the item with the unique color. During the test phase, all observers searched for a blue item among gray items. Spatial positioning of the items was randomized in all trials.

During both training phases and the test phase, three factors were varied: First, half of the search displays contained five items and half nine. Second, in half of the trials a distractor was present: in the training phases, one of the nontargets was replaced by a square; in the test phase, one of the nontargets became a diamond. Third, the line orientation inside the target shape was vertical in half of the trials and horizontal in the other half. Combination of those three variations resulted in eight different conditions which were repeated 63 times during both training and test. Consequently, there were 504 trials per phase, which were presented in seven blocks of 72 trials each. In every block, each of the 8 factor combinations was repeated 9 times in random order. The first 24 trials of the training phase were discarded as practice trials. The remaining trial and experimental procedures were the same as in Experiment 1.

Results

For both experimental phases, RTs below 200 ms and more than 3 standard deviations above the individual observer's mean per display size, distractor condition, and training condition

[6] The proneness to attentional capture, that is, the amount of distractor interference exhibited, varies considerably across individuals (e.g., Fukuda & Vogel, 2009). Implementing search mode as a within-subjects factor would further reduce any influence of this (potential) confounding factor relative to a between-subjects design with random group assignment. Search mode has already been successfully manipulated within participants previously (Lamy & Egeth, 2003).

were discarded as outliers (overall, 1.84% of trials). Similarly, error trials were discarded (3.96% of all trials). An ANOVA of the error rates with the within-subjects factors training, display size, and distractor condition did not reveal any significant effects for the training phase (all *p*s > .08). The error rates in the test phase were analyzed by an analogous ANOVA. This revealed a main effect of distractor condition, F (1, 15) = 8.25, $p < .05$, MSE = 3.71, $\eta^2_p = .36$, which was qualified by a significant interaction with training condition, F (1, 15) = 5.57, $p < .05$, MSE = 1.02, $\eta^2_p = .27$. As can be seen in Table 1, observers made more errors when a distractor was present rather than absent, with this effect being more pronounced following the singleton mode training, compared to the feature mode training. To rule out that a possible RT interference reduction in the test phase was due to observers having traded accuracy for speed on distractor-present trials and therefore exhibited an interference pattern in their error rates, we compared RT interference with error interference. If RT interference reduction were associated with increasing error interference, one should find a negative correlation between the respective scores. However, RT interference was not significantly correlated with error interference, in either training condition (feature mode training: $r = .03$, *ns*; singleton mode training: $r = .32$, *ns*).

The RTs of the *training phases* were entered into an ANOVA with the within-subjects factors training, display size, and distractor condition. This revealed a main effect of distractor condition, F (1, 15) = 9.87, $p < .01$, MSE = 1.029.33, $\eta^2_p = .40$. As can be seen in Figure 7, during both the singleton mode training (22.24 ms; t (15) = -2.95, $p < .05$) and the feature mode training (13.16 ms; t (15) = -2.69, $p < .05$), the observers were significantly distracted by the shape distractor. Although the interference appeared more pronounced with singleton mode training than with feature mode training, the training x distractor condition interaction was not significant, F (1, 15) = 2.47, $p = .14$, MSE = 258.39, $\eta^2_p = .14$. Interference in both training phases was not influenced by the order of the experimental sessions: The observers in the feature mode training phases showed comparable interference independently of whether they started with a feature mode session (13.71 ms) or had already performed a singleton mode session on the previous day (12.61 ms), t (14) = 0.11, *ns*. The same was true for the singleton mode observers (24.35 ms vs. 20.14 ms; t (14) = 0.27, *ns*).

The RTs of the *test phase* were analyzed by an analogous ANOVA. This revealed no significant main effect of distractor condition, F (1, 15) < 1, $p = .43$, MSE = 211.31, η^2_p = .04, and no significant training x distractor condition interaction, F (1, 15) < 1, $p = .73$, MSE = 106.47, $\eta^2_p = .01$. As shown in Figure 7, neither for the feature mode group (1.49 ms; t

(15) = -0.39, *ns*) nor for the singleton mode group (2.72 ms; *t* (15) = -1.14, *ns*) was there significant interference. See Tables 2 and 3 for additional results not related to interference.

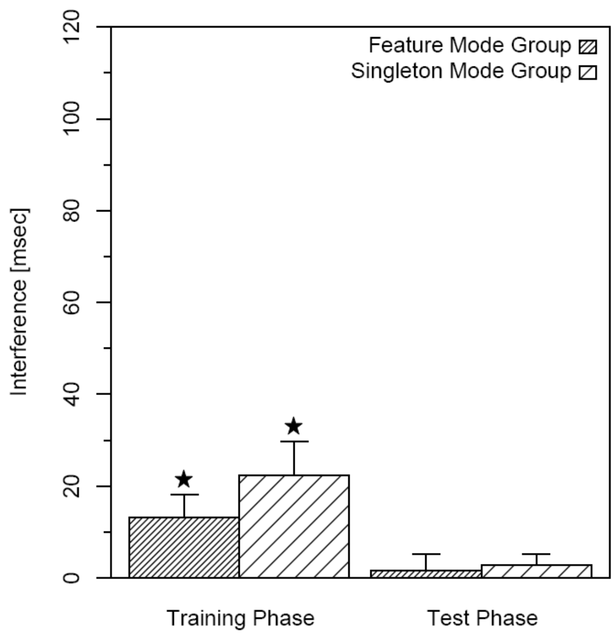

Figure 7. Experiment 5: Mean interference caused by the square-shaped distractor in the training phase and by the diamond-shaped distractor in the test phase, for the two search mode conditions. Significant interference effects are marked by an asterisk. Error bars denote one standard error of the mean interference.

Discussion

Experiment 5 examined whether hierarchical feature weighting underlies interference reduction at least for the shape dimension, by presenting featurally different (cross-dimensional) shape distractors during training and test, respectively. The main results are in line with hierarchical feature weighting: while there was significant interference in both training phases, there was no significant interference during the test phase, even though the feature of the distractor changed from square to diamond. Thus, apparently, the observers acquired a suppression strategy for the shape dimension during both training phases, which they then carried over to the test phases – thus minimizing interference by the test phase shape distractor, which was defined by a different shape feature to its training phase counterpart.

In contrast, the results of Experiment 5 are difficult to reconcile with the notion that it is the implementation of a feature mode that underlies interference reduction: Although the respective training phase highly encouraged the use of a feature mode, there was significant interference, which was not markedly smaller than the interference observed during the singleton mode training phase, as indicated by a non-significant interaction of training phase and distractor condition. These results are more in line with the acquisition of a practice-dependent suppression strategy being the main factor underlying interference reduction: During the training phases, observers in both groups had had little distractor exposure and thus little opportunity to establish an efficient suppression strategy. However, with extended exposure to distractors, the suppression strategy became increasingly routinized, up to a level that permitted interference to be completely prevented during the test phase. The fact that interference could also be reduced to a non-significant level after singleton mode training demonstrates once more that interference reduction is also possible in this search mode.

GENERAL DISCUSSION

The present study investigated three core questions concerning the nature of top-down control in visual search: (i) Do qualitatively different search modes underlie interference reduction? (ii) What is the contribution of distractor practice to interference reduction? (iii) How specific is attentional top-down control in interference reduction?

Qualitatively different search modes vs. continuous top-down control settings

The notion that there are two qualitatively different search modes and that the implementation of a feature mode is the causal factor underlying interference reduction is not supported by the present findings: Without distractor practice, the feature mode observers in Experiment 2 could not prevent attentional capture during the test phase; rather, they showed a comparable degree of interference to the singleton mode observers, demonstrating that the implementation of a feature mode as such is not the causal factor for interference reduction. With regard to the question whether attentional control in feature mode is based on direct selection from the relevant feature map or on continuous feature weighting (see Figure 1a), the present results argue for the latter alternative: While interference in the feature mode training phases was not significant in Experiments 3 and 4 (similar to Leber & Egeth, 2006b), it was significant in Experiments 1 and 5. Hence, interference in this search mode cannot be prevented as consistently or effectively as would be expected if top-down selection were based directly on the relevant feature map, completely ignoring activity from all other feature maps. This would appear to be in line with Bacon and Egeth (1994), who already conceived of the possibility that bottom-up activations could, in some situations, overwhelm top-down control even if the system is set to operate in feature mode. The weighting interpretation is also in line with Inukai, Kawahara, and Kumada (2010) who examined nonspatial attentional capture and found that while capture was not completely eliminated in feature mode, it was weaker than in singleton mode (see also Inukai, Kumada, & Kawahara, 2010).

The finding that with sufficient distractor practice, singleton mode observers were also able to considerably reduce distractor interference[7] implies that this 'search mode' does not constitute a discrete state (of relying solely on stimulus salience). Note that already Leber and Egeth (2006b), in line with findings of Lamy et al. (2006), suggested that observers may abandon a 'pure' singleton mode if the singleton target feature is fixed, rather than varying unpredictably. However, if top-down and bottom-up factors may be combined with each other without any clear transition, the question arises what is gained theoretically by postulating distinct search modes. The present results suggest that observers have a continuum of, rather than just two, 'search modes' at their disposal, ranging from very strong top-down control to basically no top-down control. Attentional capture on a given trial would therefore depend on the relative strength of top-down control settings and bottom-up salience activations, as suggested by Guided-Search-type models (e.g., Wolfe, 1994; Müller et al., 1995). The evidence that the feature mode training induced a particularly strong top-down weighting (as indicated by a more rapid and effective interference reduction compared to the singleton mode training) might be owing to an interaction between the presence of cross-dimensional distractors and other display characteristics: For instance, the feature mode observers may have had a particularly high incentive to apply top-down control as two unique shapes in their training phase constituted intra-dimensional distractors with a prevalence of 100% (see e.g., Müller et al., 2009, for distractor prevalence effects).

Causal role of distractor practice for interference reduction

Taken together, the present findings suggest that repeatedly encountering distractors is necessary for interference reduction to become effective. First, if no distractors were presented during the training phases (Experiment 2), observers in both search groups showed significant, and indeed comparable, interference during the test phase. Moreover, in the test

[7] Note that we observed considerable interference reduction during the singleton mode training not only for Experiment 1, but also for Experiments 3–5: In Experiment 3, interference dropped from 81.35 ms (first half of the training phase) to 39.01 ms (second half of the training phase); in Experiment 4, there was a reduction from 71.90 ms to 37.05 ms; and in Experiment 5, singleton mode observers reduced interference from 31.09 ms to 12.81 ms. We pooled the singleton mode data across Experiments 3–5 to statistically examine the time course of interference reduction from the first half of the training phase to the second half of the test phase. As six observers had participated in more than one experiment, their two respective data sets were collapsed into a single one by averaging over the interference values. Subsequently, the interference values were examined by a repeated-measures ANOVA with the single factor epoch of experiment. As revealed by a significant main effect, F (2.45, 78.23) = 12.96, $p < .001$, MSE = 1,280.70, $\eta^2_p = .29$ (Greenhouse-Geisser-corrected values), there was a considerable change of interference over time: interference was significantly higher in the first half of the training phase (epoch 1: 60.93 ms) compared to all other epochs (epochs 2–4: 27.30, 21.55, and 15.79 ms respectively) (all ps < .01, Bonferroni-corrected); no other pairwise comparisons were significant.

phase, attentional capture was significantly more marked without prior distractor practice (Experiment 2) than with distractor practice (Experiment 1), for both search groups. Second, there was a considerable interference reduction as a function of (increasing) practice for both search groups (Experiments 1 and 5). In fact, with sufficient practice, the singleton mode observers in Experiment 5 could reduce interference to the same, non-significant level achieved by feature mode observers.

Specificity of top-down interference reduction in feature mode

Concerning the specificity of top-down control in feature mode, the present results suggest that top-down control is not based on independent feature weighting or on direct selection from the relevant feature map: Observers trained to use a feature mode were as unable as singleton mode observers to effectively prevent interference from distractors defined in the same dimension as the target (Experiment 3), although they could prevent interference from cross-dimensional distractors (Experiment 1).

This is at variance with studies that used temporal search tasks (e.g., Folk et al., 2002; Lamy et al., 2004), reporting that interference by intra-dimensional distractors could be completely prevented in feature mode. The present findings also differ from temporal search results with regard to carry-over effects of an induced search mode to 'option trials': While Leber et al. (2009), using a temporal search task, found carry-over of search mode despite changing all stimulus features, we did not consistently observe the same for a standard visual search task (e.g., Experiment 4). In general, the present results hint at a difference between temporal and standard visual search tasks, which requires additional research.

As Experiment 3 had shown that top-down interference reduction is not based on independent feature weighting or feature selection, we more closely examined an alternative hypothesis suggested by the dimension-weighting account (e.g., Müller et al., 1995; Found & Müller, 1996). According to this account, feature weighting is hierarchically organized, that is, up- or down-modulation of one specific feature in a given dimension will also influence other features in the same dimension to a certain degree (see Figure 1b). In line with this assumption, Experiment 5 demonstrated that when confronted with distractors defined in the shape dimension, both feature and singleton mode observers can utilize distractor suppression practice with one shape feature to avoid or minimize interference by another shape feature. However, this was not observed for the color dimension: In Experiment 4, feature mode observers could not utilize distractor suppression practice with one color feature to avoid capture by another color feature (though their interference effect was not significantly increased for the changed distractor feature). These divergent result patterns between Experiments 4 and 5 may be due to the color dimension being organized differently to other dimensions (cf. Found & Müller, 1996; see also Nothdurft, 1993; Wolfe, Chun, & Friedman-Hill, 1995). Feature weighting within the color dimension might be more independent than, for instance, feature weighting in the shape dimension. That is, when weight is assigned to a specific color, the other colors may gain less weight compared to alternative shape features when weight is assigned to a specific shape. Further research is needed to achieve a better understanding of differences between attention to color and attention to shape or orientation (or, respectively, of shielding against distraction from stimuli defined in those dimensions).

CONCLUSION

The present study investigated several properties of attentional top-down control in visual search: are there different search modes? What is the role of practice for top-down control? How specific is top-down control? We investigated these issues in the distractor paradigm, in which two salient items are presented, only one of which is relevant for solving the task. Taken together, the present results cast doubt on the notion of two qualitatively different search modes, with the adoption of a feature mode being critical for interference reduction. Instead, our findings suggest that distractor practice is a decisive factor for resisting attentional capture in both feature and singleton mode operation. This is in line with Guided-Search-type models which assume a single processing mode (e.g. Wolfe, 1994; Müller et al., 1995), and adds further support to the notion that the acquisition of an effective suppression strategy is necessary for interference reduction (Müller et al., 2009). When paying attention to one specific feature so as to attenuate or prevent interference by other features, the present results favor a hierarchically organized weighing mechanism (as suggested by the dimension-weighting account; Müller et al., 1995; Found & Müller, 1996) over a completely independent feature weighting mechanism. Admittedly though, in the present study, hierarchical feature weighting was unequivocally supported only for the shape, but not the color, dimension, possibly pointing to fundamental differences in feature coding between the two dimensions.

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2.2 Early top-down control over saccadic target selection: Evidence from a systematic salience difference manipulation

SUMMARY

Time has been identified as an important factor of influence on top-down shielding from distraction in attentional and oculomotor selection: For instance, according to the *timing account* of visual selection (e.g., van Zoest et al., 2004), early (i.e., short-latency) eye movements are mostly stimulus-driven, whereas late (i.e., long-latency) eye movements are subject to top-down control. The aim of the second study presented in this dissertation was to systematically investigate the degree to which even early, short-latency, eye movements can be influenced by top-down control. To this end, the salience difference between a target stimulus and an irrelevant distractor stimulus was parametrically manipulated; observers were presented with two distractors of comparable salience to the target and with three distractors more salient than the target (with different levels of salience difference). The analysis focused on the 25% eye movements with the shortest saccadic latencies; three different indicators of top-down control were investigated. First, it was important to look at distractors of comparable salience to the target; a pure bottom-up account of early saccadic target selection would predict that if target and distractor are of comparable salience, they should have a comparable early selection probability. However, in the present study, this was not the case: Distractors of comparable salience to the target attracted considerably fewer early fixations than the target. Second, distractors more salient than the target were investigated; a pure bottom-up account of early saccadic target selection would expect those distractors to attract the vast majority of early fixations. However, in the present study, this was not true for all distractors more salient than the target: If the distractor was only somewhat more salient than the target, it again attracted fewer early fixations than the target. Third, the salience difference with equal selection probability for target and distractor was estimated; this can be taken as a quantitative indicator of the top-down control applied. This showed that a distractor had to have a considerable bottom-up salience advantage over the target to be selected with equal probability to the target. Taken together, the results of the second study presented here suggest that a non-negligible degree of top-down control operates already in the shortest latency range.

CONTRIBUTIONS

HG, AIK, and MZ conceived the research. **HG** and MZ designed the experiments. **HG** collected and analyzed the data. **HG** discussed the results with MZ and HJM. **HG** wrote the paper. MZ and HJM commented on and revised the paper.

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Early top-down control over saccadic target selection: Evidence from a systematic salience difference manipulation

Harriet Goschy

Ludwig-Maximilians-Universität München, Munich, Germany,

and Graduate School of Systemic Neurosciences, Planegg-Martinsried, Germany

A. Isabel Koch

Ludwig-Maximilians-Universität München, Munich, Germany,

and Graduate School of Systemic Neurosciences, Planegg-Martinsried, Germany

Hermann J. Müller

Ludwig-Maximilians-Universität München, Munich, Germany,

and Birkbeck College, University of London, London, UK

Michael Zehetleitner

Ludwig-Maximilians-Universität München, Munich, Germany

ABSTRACT

Previous research on the contribution of top-down control to saccadic target selection has suggested that eye movements, especially short-latency saccades, are primarily salience-driven. The present study was designed to systematically examine top-down influences as a function of time and relative salience difference between target and distractor. Observers performed a saccadic selection task, requiring them to make an eye movement to an orientation-defined target, while ignoring a color-defined distractor. The salience of the distractor was varied (five levels), permitting the percentage of target and distractor fixations to be analyzed as a function of the salience difference between target and distractor. This analysis revealed the same pattern of results for both the overall and the short-latency saccades: When target and distractor were of comparable salience, the vast majority of saccades went directly to the target; even distractors somewhat more salient than the target led to significantly fewer distractor, as compared to target, fixations. To quantify the amount of top-down control applied, we estimated the point of equal selection probability for target and distractor. Analyses of these estimates revealed that, to be selected with equal probability to the target, a distractor had to have a considerably greater bottom-up salience compared to the target. This difference suggests a strong contribution of top-down control to saccadic target selection – even for the earliest saccades.

INTRODUCTION

While most current theories of visual search take the possibility of top-down control over the allocation of attention into account (e.g., Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Müller & Krummenacher, 2006; Navalpakkam & Itti, 2005; Wolfe, 1994), there is still considerable debate about the temporal starting point of top-down control: According to the current version of the *automatic-attentional-capture account* (Theeuwes, 2010), initial attentional selection in parallel search is completely stimulus-driven. Only later in processing, that is, after attention has been shifted to the most salient item, can top-down processing have an influence, for instance, by reducing the time it takes to disengage attention from the selected item (e.g., Born, Kerzel, & Theeuwes, 2011; Theeuwes, Atchley, & Kramer, 2000). Similarly, van Zoest, Donk, and Theeuwes (2004) have argued for a *timing account* of visual selection, which assumes that short-latency eye movements are completely stimulus-driven (i.e., they go to the most salient item in the field even if this is not the target stimulus), whereas long-latency eye movements may be influenced by top-down control. Accordingly, early attentional processing is stimulus-driven, while slower attentional deployment can be top-down influenced (see also Hickey, van Zoest, & Theeuwes, 2010, and Hunt, von Mühlenen, & Kingstone, 2007, for similar suggestions). More recently, it has been suggested that this pattern of results arises because at the time at which early saccades are initiated, visual processing is not yet complete, with the set of potential targets being limited to those that have been processed thus far (de Vries, Hooge, Wiering, & Verstraten, 2011; but see Siebold, van Zoest, Meeter, & Donk, in press).

Top-down versus bottom-up factors in visual attention are often investigated in variations of the so-called additional-singleton paradigm (Theeuwes, 1992). In this task, observers perform a visual search for a target item surrounded by several nontargets, while in a certain proportion of trials a task-irrelevant (but usually very salient) distractor is presented in addition to the target. Attentional capture by this task-irrelevant distractor is then quantified as response time (RT) slowing in the presence, compared to absence, of the irrelevant distractor. If a saccadic selection variant of this task is used (where observers are asked to make a speeded saccade to the target), attentional capture is operationalized as the percentage of first saccades that went to the distractor, rather than to the target. Saccadic target selection can be taken as a reliable indicator of covert attentional deployment, as there is a close coupling between the attentional and saccadic systems (e.g., Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995).

Van Zoest et al. (2004) used the saccadic selection variant of the additional-singleton paradigm to test their timing account of visual selection. They presented observers with a target and a distractor of comparable salience, both defined in the orientation dimension (i.e., both target and distractor were tilted 45° relative to vertical nontargets – one to the left, the other to the right), and asked them to make a saccade towards the pre-specified target stimulus. The proportion of first saccades that went to the target (rather than the distractor) increased with increasing saccadic latency. As an equal amount of the short-latency saccades went to the target and, respectively, the distractor, van Zoest el al. (2004) concluded that early saccadic target selection is completely salience-based, whereas top-down control can have an influence only later in time (see also van Zoest & Donk, 2005, for similar results). Similarly, van Zoest and Donk (2006) manipulated both distractor salience (high vs. low) and target-distractor similarity (high vs. low) independently, assuming that the former would influence stimulus-driven control and the latter goal-driven control. For the short-latency saccades, there was only an effect of distractor salience, but no effect of target-distractor similarity, again suggesting that goal-driven control can influence only late saccades, but not the earliest ones.

However, scrutiny of the results of van Zoest et al. (2004) suggests that this might not be the whole story: For instance, in their Experiment 4, observers had to make a saccade to an orientation target while one of three orientation distractors – one less, one equally, and one more salient relative to the target – could be present. As can be seen from Figure 6 of van Zoest et al. (2004), even with the more salient distractor, around 40% of the short-latency saccades went to the target and not to the distractor. However, this observation was not expressly noted or considered further, and van Zoest et al. (2004) drew the strong conclusion that "saccadic visual selection is initially completely stimulus driven" (p. 755). Additional indications of (possible) early top-down control are evident from a more recent experiment of van Zoest and Donk (2008), who presented their observers with color and orientation singletons. The identities of the target and distractor were switched across conditions, which allowed for the calculation of 'difference scores', that is: how many more saccades go to a singleton if it is defined as a target than if it is defined as a distractor. Analysis of difference scores as a function of saccadic latency revealed these scores to increase as saccade latencies became longer, suggestive of an increasing influence of top-down control over time. However, even for the shortest latencies, the difference score was still significantly different from zero – which led the authors to concede some "limited goal-driven selectivity" (p. 1561) even for short-latency saccades.

On this background, the present study was designed to (i) corroborate indications of "limited" goal-driven control of early saccadic selection (to be universally accepted) and (ii) quantitatively determine the strength of goal-driven selectivity in experiments systematically varying target-distractor relative salience. To our knowledge, there have been no previous studies of the contributions of top-down and bottom-up factors to saccadic target selection that involved manipulation of the relative salience (difference) between target and distractor beyond the broad categories "more salient", "comparably salient", and "less salient" (as, e.g., in van Zoest et al., 2004). Arguably, though, parametrically manipulating the salience difference between target and distractor – for instance, introducing various levels of "more salient" – can offer new insights into the potential top-down controllability of short-latency saccades and may yield a quantitative indicator for the degree of top-down control applied.

To illustrate, when examining percentage target and distractor fixations as a function of the parametric salience difference between target and distractor, a different pattern of results would emerge when early saccades are completely stimulus-driven compared to when they are, to some extent, top-down controllable (see Figure 1).

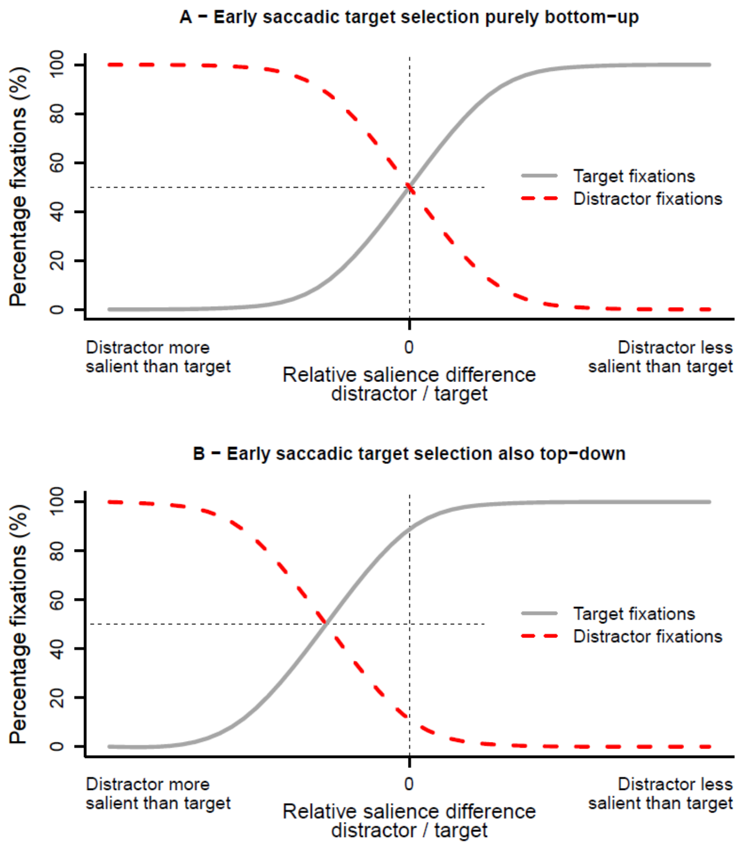

Figure 1. Qualitative predictions for percentage early target and distractor fixations as a function of salience difference between target and distractor: (A) Predicted distribution if early saccadic target selection is purely bottom-up driven. (B) Predicted distribution if early saccadic target selection can be top-down influenced.

A pure stimulus-driven account and, respectively, a top-down account of early saccadic selection make three divergent predictions when taking into account the relative salience difference between target and distractor: First, if target and distractor are of comparable salience (i.e., having a salience difference of zero), a purely stimulus-driven account of early saccadic selection would predict an equal amount of target and distractor fixations (50% : 50%): In this case, both target and distractor should generate similar peaks (in terms of both rise time and strength) on a bottom-up salience map purely based on feature contrast computation (e.g., Itti & Koch, 2000), and should consequently have a comparable selection probability. By contrast, if there were top-down control over short-latency saccades, considerably more saccades should go to the target than to the distractor when they are of comparable salience: Most top-down models of visual attention assume that salience-based feature or dimension contrast maps can be top-down modified prior to their integration into a master salience map (e.g., Müller, Heller, & Ziegler, 1995; Wolfe, 1994). Hence, even if target and distractor were of comparable bottom-up salience, observers could increase the weighting of the target feature or dimension (and/or decrease the weighting of the distractor feature or dimension) and therefore increase the target's influence on the master salience map, resulting in an increased selection probability compared to the distractor.

A second divergent prediction concerns the point of equal selection probability: As mentioned above, a pure stimulus-driven account of early saccadic selection would suggest that target and distractor are selected with comparable probability if they are of comparable bottom-up salience. By contrast, a top-down account of early saccadic selection would suggest that the point of equal selection probability (i.e., point at which the percentage target and percentage distractor fixation functions intersect) is shifted to a salience difference at which the distractor is more salient than the target (see Figure 1b). The degree to which this intersection point is shifted leftwards relative to $x = 0$ can serve as a quantitative indicator of the top-down control applied.

The third and final divergent prediction between a stimulus-driven account and a top-down account of early saccadic selection is related to salience differences at which the distractor is more salient than the target: A purely bottom-up account of early saccadic selection would assume that once the distractor is more salient than the target, the majority of short-latency saccades should go to the distractor (see Figure 1a).[8] By contrast, if there were top-down control over early saccadic selection, there should be cases in which the distractor is more salient than the target and still the majority of short-latency saccades go to the target (see Figure 1b). Note that these three predictions are not independent of each other; for instance, if the point of equal selection probability is shifted to a salience difference where the distractor is more salient than the target (prediction 2), there should (also) be distractors more salient than the target which give rise to more target than distractor fixations (prediction 3). Also note that these predictions are based on relative salience values (e.g., how much more salient is the distractor compared to the target), irrespective of the absolute salience values of target and distractor.

The aim of the present study was to systematically examine the influence of the relative salience difference between target and distractor on the percentage of target and distractor fixations. The main focus was on short-latency saccades, that is: to which degree can even those relatively early saccades be influenced by top-down control? Examination for the presence versus absence of early top-down control followed the three divergent predictions made by a purely stimulus-driven early saccadic selection model and a top-down

[8] Note that following a deterministic interpretation of attentional capture (Theeuwes, 1992, 2010), one could argue that not only the majority of early saccades should go to the most salient item, but in fact all early saccades should go to the most salient item. In this case, Figure 1a would actually be a step function. However, recent evidence suggests that salience-based selection is probabilistic rather than deterministic (Zehetleitner et al., 2013).

early saccadic selection model as outlined above (see also Figure 1). Additionally, a quantitative indicator of top-down control was determined: the estimated intersection point between the functions of percentage target and percentage distractor fixations (i.e., the salience difference at which both target and distractor are selected with an equal probability). The analyses conducted followed a two-step approach: In step 1, the overall target and distractor fixations were examined for these indicators of top-down control. Note that for responses later in time or responses averaged across time, both bottom-up and top-down accounts would allow for saccadic selection to be primarily goal-driven, as has been repeatedly demonstrated (e.g., Siebold, van Zoest, & Donk, 2011; van Zoest et al., 2004; van Zoest & Donk, 2006, 2008). Accordingly, the three top-down indicators (described above) should be clearly observable in the overall data. In step 2, only fixations following short-latency saccades were examined for the three indicators of top-down control – as positive findings for short-latency trials (rather than just for the averaged data) are crucial for deciding between bottom-up and top-down accounts of early saccadic selection.

Given the three divergent predictions, the present study focused on distractors that were similar in salience to or more salient than the target (for distractors less salient than the target, both models make the same predictions, namely: more target than distractor fixations). The present study consisted of two parts: a salience measurement experiment and a saccadic selection task in which participants were asked to make a speeded saccade to an orientation target and ignore one of five possible color distractors present on every trial. The relative saliences of these five different color distractors were determined in a go/no-go detection experiment, in which observers were asked to discern the presence versus absence of the orientation (the later target) feature and the five color (the later distractor) features. Note that in this salience measurement experiment, both the orientation (target) feature and the color (distractor) features were presented as *to-be-detected target singletons*; only in the eye tracking experiment was the target feature then presented as the response-relevant target and the distractor features as irrelevant distractors. The differences in detection response times (RT) between the target feature and each of the five distractor features was taken as an estimate of the relative salience difference between target and the respective distractor (see Zehetleitner, Koch, Goschy, & Müller, 2013, for a similar salience measurement procedure). Salience difference was calculated as detection $RT_{distractor}$ – detection RT_{target}.[9] If a distractor

[9] Note that this order (i.e., detection $RT_{distractor}$ – detection RT_{target}) is arbitrary. Of course salience difference could also be calculated as detection RT_{target} – detection $RT_{distractor}$. In this case a positive salience difference would correspond to the situation of the distractor being more salient than the target. Accordingly, the prediction and result plots presented here would be mirrored around the y-axis.

feature was detected faster than the target feature in the salience measurement experiment, this resulted in a negative salience difference, indicative of the distractor being more salient than the target. Additionally, the relative salience difference between distractor and target can be taken to be the greater the larger the difference in detection RTs between the target and distractor feature.

Examining percentage target and distractor fixations as a function of the relative salience difference between target and distractor allowed us to critically investigate the divergent predictions made by a purely stimulus-driven early saccadic selection model and a top-down early saccadic selection model concerning the following three questions: (a) How are target and distractor fixations distributed if target and distractor are of comparable salience? (b) At which salience difference do target and distractor have a comparable selection probability? (c) Are there negative salience differences (i.e., distractor more salient than target) for which there are more target than distractor fixations?

METHOD

Participants

Eight (6 female, all right-handed) observers with a median age of 26 years (range: 22-31 years) took part in the experiment. They were recruited from the participant panel of the Chair of Experimental Psychology (Ludwig-Maximilians-Universität München, Munich, Germany) and were either paid for their participation (8 Euros / hour) or received a course credit. All of them reported normal or corrected to normal visual acuity and color vision.

Apparatus

The experiment was conducted in a sound-isolated, dimly-lit cabin with black interior. The stimuli were generated using a ViSaGe system (Cambridge Research Ltd., UK) and the Experimental Toolbox (Reutter & Zehetleitner, 2012) for MATLAB (The MathWorks, Inc.), controlled by a personal computer running under the Windows XP operating system. Stimuli were presented on a 22-inch Mitsubishi Diamond Pro 2070SB monitor (screen refresh rate of 120 Hz, screen resolution of 1,024 x 768 pixels). Observers viewed the monitor from a distance of about 70 cm. A chin and forehead rest was used to minimize head movements. Stimulus displays were viewed binocularly and eye movements were recorded from the right eye, at a sampling rate of 1000 Hz, by means of an EyeLink 1000 Desktop Mount eye tracker (SR Research Ltd., Canada), which was positioned below the display the participants were looking at. For saccade detection, the standard 'cognitive configuration' setting of the

EyeLink-internal detection algorithm was used (velocity threshold of 30°/s and an acceleration threshold of 8,000°/s²).

Stimuli

The stimulus display was presented on a black background and consisted of gray (RGB: 127, 127, 127; CIE [Yxy]: 13.6, .28, .32) vertical bars (0.25° of visual angle wide, 1.35° high). The geometric centers of these bars were equidistantly arranged on the circumferences of three concentric (imaginary) circles. These circles had a radius of 2°, 4°, and 6° and encompassed 6, 12, and 18 bars, respectively; a further gray bar occupied the position in the center of the three circles. See Figure 2 for an example stimulus display.

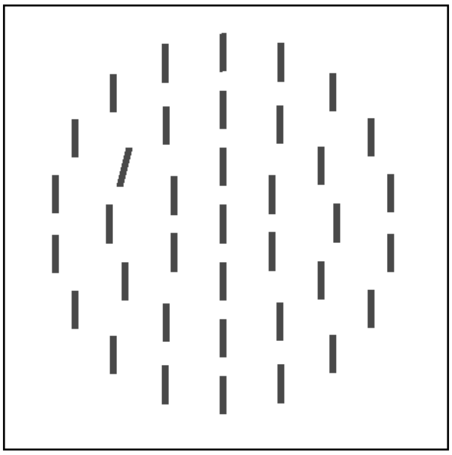

Figure 2. Illustration of a stimulus display: In the salience measurement experiment, the target was either defined by orientation (as in the example) or by color. In the eye tracking experiment, the target was always defined by orientation and, additionally, a color distractor was present on every trial (not depicted in the example).

Salience measurement. In the salience measurement experiment, the target, if present, could be defined either by orientation or by color. If it differed from the nontargets in orientation, it was tilted 12° to the left or to the right (each in a random half of the trials). If it differed from the nontargets in color, one of five different color targets of varying salience was presented. These color features represented various saturations between red and the gray of the nontargets and were matched for luminance (see Table 1 for RGB values and CIE coordinates of the color features).[10] Color 1 had the strongest red saturation, and red

[10] During pre-experimental testing, the color and orientation features introduced in the present experiment had been evaluated in two separate go/no-go detection experiments in which display size was manipulated (each with n = 16 participants, one with six color features, one with six orientation features). The set size manipulation was intended to ensure that the features introduced in the present experiment could be detected ‘efficiently’. The results revealed both the orientation (target) feature (-0.39 ms/item) and the five color (distractor) features (0.03 ms/item – 1.54 ms/item) to produce search slopes significantly below 5 ms/item (all *p*s < .001), indicative of ‘efficient search’ according to standard criteria (e.g., Wolfe, 1998).

saturation decreased with increasing color number. The target items appeared randomly at one of the 12 positions on the middle circle.

Table 1
RGB values and CIE coordinates of the color features used in the experiments

Color feature	RGB	CIE [Yxy]
Color feature 1	252, 0, 21	14.2, .62, .34
Color feature 2	180, 100, 106	13.3, .40, .31
Color feature 3	171, 104, 110	13.7, .37, .31
Color feature 4	167, 106, 112	13.8, .36, .31
Color feature 5	163, 108, 114	14.3, .35, .31

Eye tracking experiment. In the eye tracking experiment, the target item was always defined by orientation and was tilted 12° to the left or to the right (each in a random half of the trials). The five color features from the salience measurement experiment (see Table 1) were used as distractor colors in this experiment. Both target and distractor always appeared at two different of the 12 positions on the middle circle. To ensure that it would later be possible to reliably differentiate between target and distractor fixations in the data analysis, the following restriction was made for the distractor positions: The target position was randomly chosen out of the 12 possible positions on the middle circle; the distractor position was then chosen to be either shifted three or five positions to the left or to the right from the target (each in a random quarter of the trials).

Design

Salience measurement. In the salience measurement experiment, six different target features were presented: One orientation feature, and five color features. Each of the six target features was presented 80 times and targets were present in half of the trials. Overall, this resulted in 960 trials, which were presented in 12 blocks à 80 trials as follows: In each block there were 40 target-present and 40 target-absent trials. Feature dimension was blocked, that is, there were two orientation blocks and 10 color blocks. Each color feature was presented equally often during each color block (i.e., 8 times). Overall block presentation order and trial presentation order within the blocks was randomized.

Eye tracking. In the eye tracking experiment, the orientation target was present on every trial. In addition, one of five possible color distractors was also present on every trial. Each of the five distractor features was presented 128 times. Overall, this resulted in 640 trials, which were presented in 8 blocks à 80 trials. In each block, each distractor feature was presented 16 times in random order.

Procedure

The observers participated in two experimental sessions on two consecutive days, conducted at the same time of day: on the first day in the eye tracking experiment; on the second day in the salience measurement experiment. This time distance was introduced to prevent carry-over effects from the eye tracking task to the salience measurement task, in which the previous distractors were presented as response-relevant targets. Prior to each experiment, all observers received both written and oral instructions. In both experiments, participants were told to perform as fast and accurately as possible.

Salience measurement. The salience measurement experiment involved a go/no-go task: Observers were asked to detect the presence of a unique target item and press the space bar on a keyboard (Empirisoft DirectIN, Empirisoft Corporation, USA) if a target item was present, using the index finger of their left or right hand. If no unique item was present, observers were instructed not to press the space bar and instead wait for the next trial to start.

Each trial started with the presentation of a white fixation cross (0.5° x 0.5°) for a random duration ranging from 700 ms to 1,100 ms. Thereupon the search display appeared and remained visible until the observer reacted, or for a maximum duration of 1,000 ms. If the response of the observer was incorrect, that is, if she or he pressed the space bar when no target item was presented or did not press the space bar when a target item was presented, the word 'Fehler' (German for error) was presented in capital letters in the center of the screen for 1,500 ms before a new trial started. If the response was correct, the fixation cross reappeared and a new trial began. At the end of each block of trials, participants were informed about their average RT and their percentage error rate in the previous block via a message on the screen. The experimental session lasted approximately 60 minutes.

Eye tracking. The eye tracking experiment involved a saccadic localization task: Observers were instructed to remain fixated on the fixation cross until the appearance of the search display and then, after display onset, make a fast, goal-directed saccade to the (orientation) target and remain fixated on it until the disappearance of the search display. In addition, they were instructed to ignore the (color) distractors and, in case the first saccade went to a distractor nevertheless, make a saccade to the target afterwards.

Each trial started with the presentation of a white fixation cross (0.5° x 0.5°) in the center of the screen for 1,000 ms. After that, the search display appeared and remained visible for 1,000 ms. Between the offset of the search display and the onset of the next fixation cross, there was a black screen intertrial interval of a random duration between 700 ms and 1,100 ms. Observers were encouraged to use this interval for briefly closing and resting their eyes, so that they could minimize blinks during the subsequent fixation cross display and the search display. In addition, participants could take short breaks between experimental blocks. Prior to each block of trials, a nine-point eye-tracker calibration was conducted. In total, the experimental session lasted approximately 75 minutes.

RESULTS

Salience measurement

Error rates were low overall (0.22% misses and 0.61% false alarms). An ANOVA over the arcsine-square-root transformed miss rates did not yield any significant differences between the six target types, ($F(5, 35) = 1.40$, $p = .25$, n.s.). Error trials and target-absent trials were excluded from the RT analysis. Subsequently, RTs more than three standard deviations above an observer's mean per target type or below 200 ms were discarded as outliers (0.85% of all trials).

To determine whether the RTs of the different target types differed significantly from each other, an ANOVA with the within-subjects factor target type (6 levels) was conducted: As can be seen in Figure 3, there were indeed significant differences among the RTs for the various target types, $F(2.41, 16.88) = 34.15$, $p < .001$, $\eta^2_p = .83$ (Greenhouse-Geisser corrected values). As expected, RTs for the color targets increased with decreasing red saturation from the first ($M = 366$ ms, $SD = 51$ ms) to the fifth color target ($M = 429$ ms, $SD = 47$ ms). The RTs for the orientation target ($M = 426$ ms, $SD = 40$ ms) were numerically similar to the RTs for the low saturation color targets number 4 and 5 (see Figure 3).

In the eye tracking experiment, the color target features from the salience measurement experiment served as distractor features and competed with the orientation target feature for the observer's attention. Therefore, we compared the RTs for the orientation target with the RTs for each color target to obtain an estimate of their relative saliences: The RTs for the orientation target were significantly slower than the RTs for the first ($t(7) = 8.51$, $p < .001$), second ($t(7) = 6.48$, $p < .001$), and third ($t(7) = 4.24$, $p = .004$) color target. This is indicative of those three color features having a higher salience than the orientation feature. As can be seen in Figure 2, the relative salience difference ($RT_{color} - RT_{orientation}$) is largest for the first color feature and decreases in magnitude for the second and third color features, while still remaining significant. By contrast, the RTs of the fourth ($t(7) = 0.62$, $p = .55$, n.s.) and fifth ($t(7) = -0.47$, $p = .65$, n.s.) color target did not differ significantly from the RTs for the orientation target. Accordingly, those two color features have a similar salience to the orientation feature.

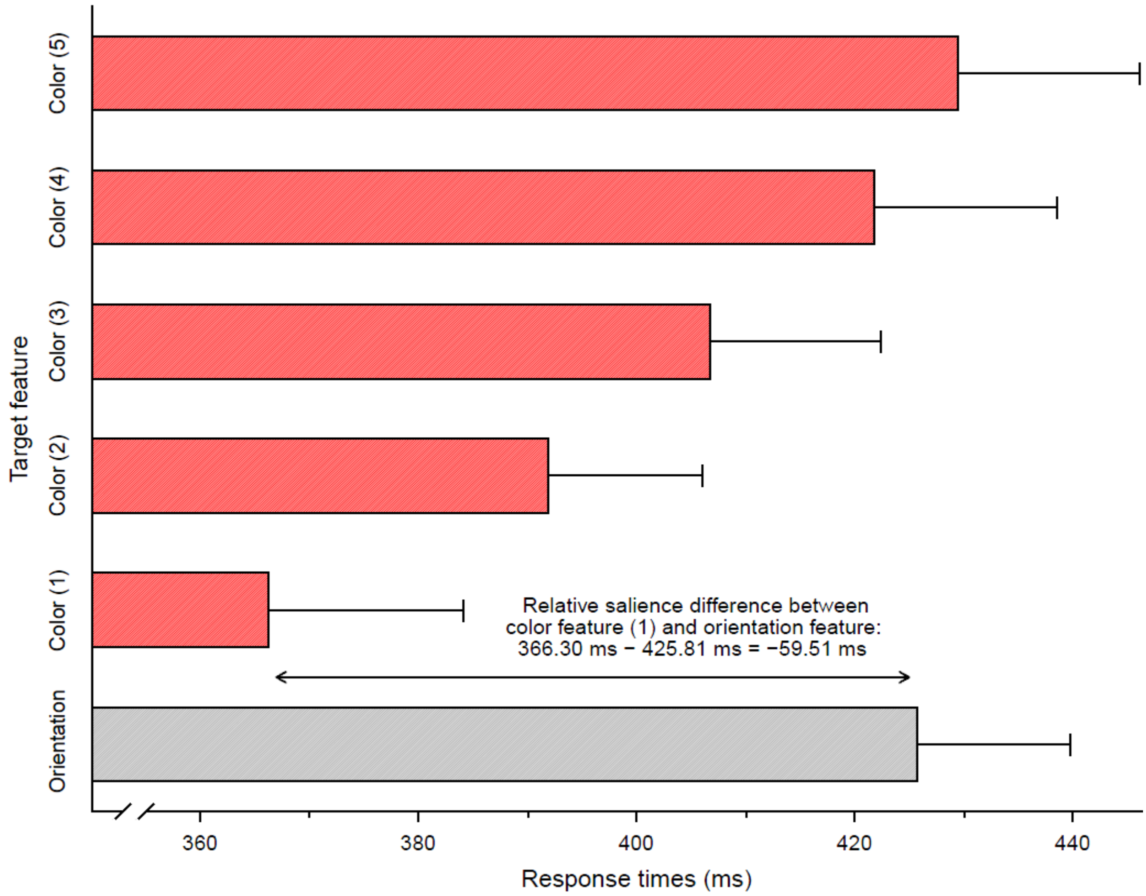

Figure 3. Target-present RTs for the six target types presented in the go/no-go salience measurement experiment. Error bars denote one standard error of the mean RT. The orientation feature was used as target, and the five color features as distractors in the eye tracking experiment. For illustration purposes, the figure also depicts the relative salience difference between color feature (1) and the orientation feature: Relative salience difference was calculated as RT for color (i) – RT for orientation. Therefore, negative salience differences denote a color feature being more salient than the orientation feature.

Eye tracking

Data preparation. For the analysis of the eye tracking data, we excluded trials on which the search display onset occurred during a saccade or the eye-tracker failed to track the participant's pupil (e.g., due to the eyes being closed). This led to a loss of 3.11% of all trials. In addition, trials with initial saccade latencies below 80 ms (2.79% of all trials)[411] and above 600 ms (0.25% of all trials) were excluded. The remaining data underwent a drift correction: Before the onset of the search display, the gaze was assumed to have rested on the fixation cross. Therefore, the deviation from the fixation cross was subtracted from the subsequent gaze position data of this trial. The fixation following the initial saccade was then assigned to the target or the distractor if its coordinates were within 2.5° of visual angle of the respective, target or distractor, location. Initial fixations, which could neither be assigned to the target nor to the distractor (10.68% of the remaining trials), were not included in the subsequent analysis.

Overall target and distractor fixations. In a first step, mean percentages of target and distractor fixations for the five distractor types were calculated. Figure 4 presents these as a function of relative salience difference calculated from the salience measurement detection RTs. The figures depicting percentage fixation distributions as a function of relative salience difference (Figure 4 and 5) permit a direct qualitative comparison with the respective predictions of bottom-up and top-down models of early saccadic target selection, as summarized in Figure 1. Recall, however, that we did not systematically investigate positive salience differences (i.e., target more salient than distractor); also, for the averaged behavior analyzed in this first step, both bottom-up and top-down accounts would allow for saccadic selection to show indications of top-down control.

Prior to statistical analysis, the percentage distractor and target fixations were arcsine-square-root transformed. An ANOVA over the percentage distractor fixations with the within-subjects factor distractor type (five levels) revealed a significant main effect, F (1.25, 8.74) = 65.43, $p < .001$, $\eta^2_p = .90$ (Greenhouse-Geisser corrected values). As can be seen in Figure 4, the mean percentage of distractor fixations increased with increasing salience of the distractor relative to the target (i.e., the more negative the salience difference became). Distractors number 4 and 5 were of comparable salience to the target, that is, they had a relative salience difference close to zero. A pure bottom-up model would predict that if two items are of comparable salience, each of them should attract attention about 50% of the time. However, this was clearly violated by the present data (see Figure 4): Distractors number 4 and number 5 both attracted significantly fewer fixations than the target, $t(7) = -10.08$, $p < .001$ and $t(7) = -11.96$, $p < .001$. Overall, only for the most salient first distractor

[11] Given the present focus on short latencies, it is important to note that of the excluded latencies below 80 ms, 92.25% did go neither to the target nor to the distractor. Including the remaining trials in the analysis would not have changed the results in any significant way.

were there significantly more distractor fixations than target fixations, $t(7) = 2.54$, $p = .04$. For distractors number 2 and 3, which were also more salient than the target (but had produced a smaller salience difference in the salience measurement experiment), a different picture emerged: Even though these two distractors were also more salient than the target, they attracted significantly fewer fixations than the target, $t(7) = -5.79$, $p < .001$ and $t(7) = -12.93$, $p < .001$. As can be seen in Figure 4, the estimated point of equal selection probability (50% : 50%) would have to be located at a relative salience difference between the first and the second distractor: By linear interpolation, the intersection point with the x-axis parallel y = 50% was estimated to occur at a salience difference of -49 ms (see Figure 4), which is clearly different from zero.

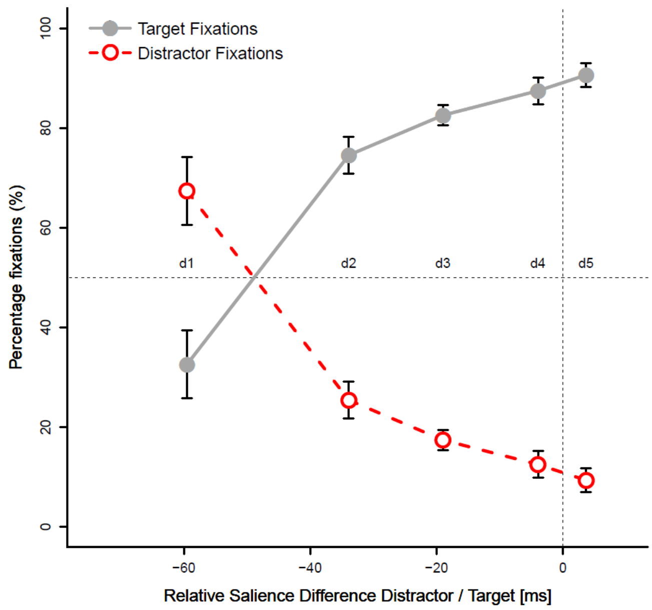

Figure 4. Mean percentage target and distractor fixations for the five distractor types, distractor 1 (d1) – distractor 5 (d5), presented in the eye tracking experiment. The percentage fixations are plotted as a function of the relative salience difference between the orientation target and the color distractor, as calculated from the salience measurement experiment (distractor RT – target RT). Error bars denote one standard error of the mean percentage fixation rate. Note that mean percentage target and distractor fixations sum to 100%, since erroneous (other) fixations were not included in the analysis.

Target and distractor fixations as a function of time. In a second step, percentage target and distractor fixations were analyzed as a function of time. To this end, quartiles for the initial saccade latencies of each participant for each distractor type (irrespective of the saccade destination) were calculated. Based on these values, the data of each participant could be sorted into one of four bins for each distractor type, each representing 25% of the data. Bin 1 contained the 25% shortest saccadic latencies for each distractor and participant, and bin 4 the 25% longest saccadic latencies. See Table 2 for the mean saccadic latencies per 25% trial bin and distractor type. Figure 5 shows the mean target and distractor fixations in these four 25% trial bins as a function of salience difference, as calculated from the salience measurement experiment. Again, these figures allow a direct qualitative comparison with the predictions of bottom-up and top-down models of early saccadic target selection (Figure 1).

Table 2

Mean saccadic latencies per 25% trial bin and distractor type [ms] (SD)

	Trial bin 1	Trial bin 2	Trial bin 3	Trial bin 4
Distractor 1	190 (14)	208 (17)	224 (21)	267 (31)
Distractor 2	209 (11)	228 (14)	244 (17)	285 (37)
Distractor 3	211 (13)	228 (14)	243 (14)	283 (28)
Distractor 4	211 (12)	229 (13)	244 (16)	288 (31)
Distractor 5	212 (12)	231 (15)	245 (18)	282 (26)

Again, the percentage target and distractor fixations were arcsine-square-root transformed. The percentage distractor fixations were analyzed by an ANOVA with the within-subjects factors distractor type (five levels) and trial bin (4 levels). This revealed a significant main effect of distractor type, F (1.31, 9.17) = 60.39, p < .001, η^2_p = .90 (Greenhouse-Geisser corrected values). Overall, as can be seen in Figure 5, distractor fixations increased with increasing distractor salience. In addition, there was a main effect of trial bin, F (1.58, 11.05) = 16.45, p < .001, η^2_p = .70 (Greenhouse-Geisser corrected values). Across all distractor types, the shorter the saccade latencies the more distractor fixations were made (see Figure 5). However, this was qualified by a significant interaction between distractor type and trial bin, F (3.28, 22.94) = 9.50, p < .001, η^2_p = .58 (Greenhouse-Geisser corrected values): As can be seen in Figure 5, the main effect of distractor type was strongest for the shortest saccadic latencies and decreased in magnitude the longer the latencies became.

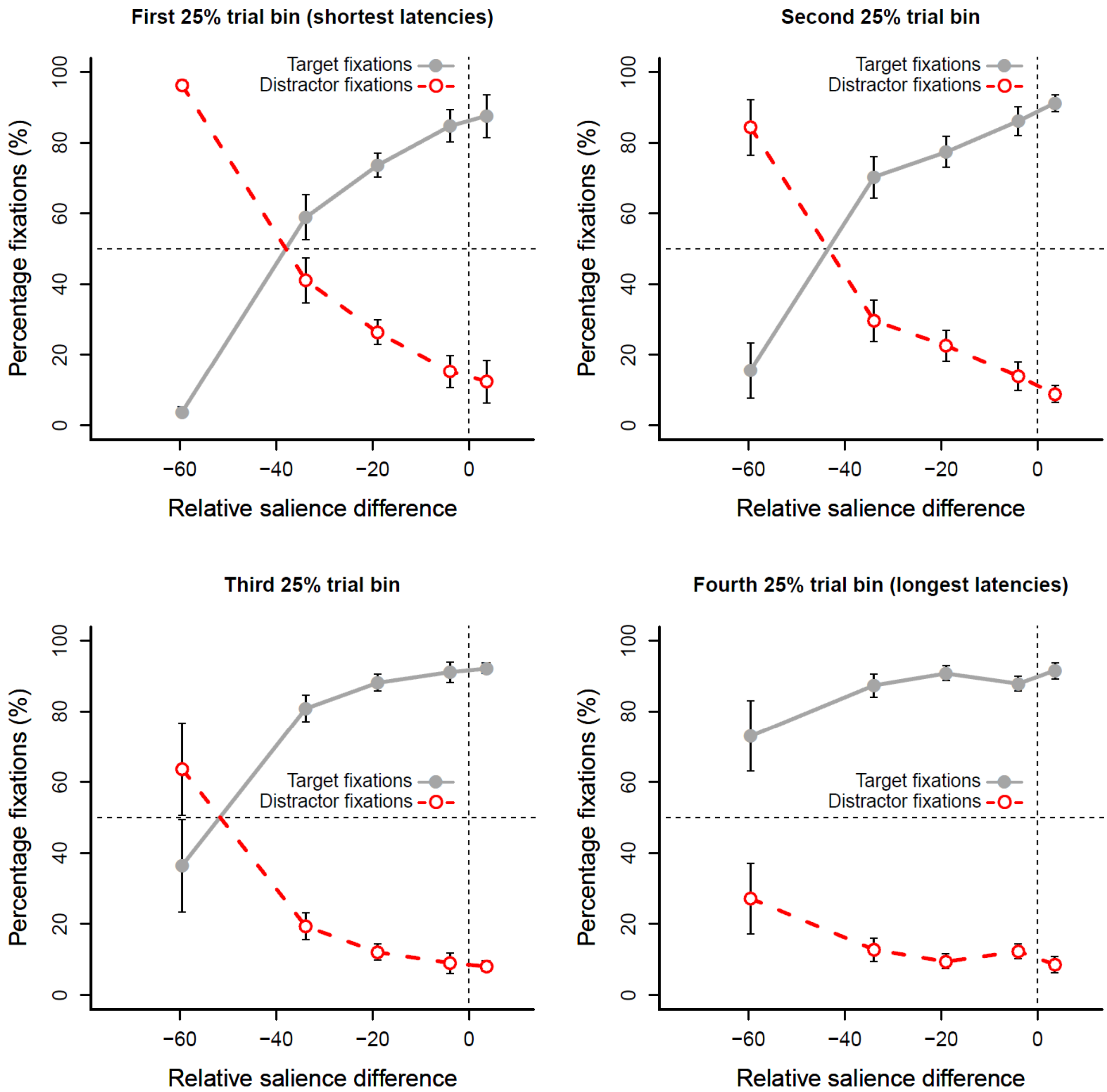

Figure 5. Mean percentage target and distractor fixations for the five distractor types plotted as a function of the relative salience difference between the orientation target and the color distractor. The four plots represent the four 25% trial bins: The first trial bin contains the 25 percent shortest saccadic latencies of each participant for each of the five distractors, the fourth trial bin the 25% longest saccadic latencies (per participant and distractor condition). Error bars denote one standard error of the mean percentage fixation rate. Note that mean percentage target and distractor fixations sum to 100%, since erroneous (other) fixations were not included in the analysis.

With regard to the central issue addressed by the present study, namely, to examine whether there is early top-down control of saccadic target selection which can be strong enough to overrule bottom-up salience, we focused on the first trial bin with the 25% shortest saccade latencies. A pure bottom-up model of early saccadic target selection would predict that for distractors number 4 and number 5, which were of comparable salience to the target, there should be an equal amount of early target and distractor fixations. However, this prediction was clearly violated by the data: Both distractor number 4 (M = 15.28%, SD = 12.81%) and distractor number 5 (M = 12.38%, SD = 17.09%) attracted significantly fewer early fixations than the target, $t(7) = -6.46$, $p < .001$, and $t(7) = -5.37$, $p = .001$, respectively. The same was true for distractor number 3 (M = 26.39%, SD = 9.70%), t (7) = -5.73, $p < .001$. Distractor number 3 had been determined to be more salient than the target in the salience measurement experiment, that is, detection RTs for this distractor had been significantly faster than RTs for the target. This is in line with the assumption that there is top-down control over early target selection (see Figure 1): With distractors more salient than the target, there can be more target than distractor fixations, even if saccadic latencies are short. For the 25% shortest latencies, only the most salient distractor number 1 caused significantly more distractor than target fixations (M = 96.25%, SD = 3.87%), $t(7) = 13.44$, $p < .001$. For distractor number 2, which was also more salient than the target (as determined in the salience measurement experiment), there was no significant difference between percentage early distractor (M = 41.14%, SD = 17.92%) and target fixations, $t(7) = -1.40$, $p = .20$, n.s.; this means that even for the 25% shortest latencies, the point of equal selection probability was shifted to a negative salience difference, as predicted by a top-down model of early saccadic selection (see Figure 1). Distractor number 2 had a relative salience difference of -34 ms; the intersection point with the x-axis parallel y = 50% (i.e., the point of equal selection probability) was estimated, by linear interpolation, to lie at a salience difference of -38 ms (see Figure 5), which is clearly different from zero.

To corroborate this finding, we calculated the intersection points for each participant (by linear interpolation based on the individual salience differences and individual percentages). This resulted in a mean estimated intersection point of -35 ms (SD = 17 ms), which differed significantly from zero, $t(6) = -5.58$, $p = .001$. (One observer had to be excluded from this analysis for having two intersection points with the x-axis parallel y = 50%).[12]

Saccadic latencies. Given the highly skewed nature of saccade latencies, the present data were log-transformed prior to being aggregated and entered into statistical analyses. An initial ANOVA of the saccadic latencies with the single (within-subjects) factor distractor type (5 levels) revealed the main effect to be significant, $F(1.35, 9.46) = 21.36$, $p < .001$, $\eta^2_p = .75$ (Greenhouse-Geisser corrected values): latencies were shortest with the most salient color distractor (number 1) being present (M = 223 ms, SD = 21 ms) and of comparable

[12] As an alternative to the linear interpolation estimation method, we fitted psychometric curves using a logistic function (with four varying parameters: center, slope, upper and lower asymptote) to the percentage target fixation curves of each subject for the first, 25% trial bin. Subsequently, we estimated points of subjective equality (i.e., points of equal selection probability) from the 50% threshold points of the psychometric curves. The mean point of subjective equality was -31 ms (SD = 15 ms), which – like the linear interpolation estimate – was significantly different from zero, $t(7) = -5.84$, $p < .001$.

magnitude with the remaining distractors (M_{d2} = 242 ms, SD_{d2} = 18 ms; M_{d3} = 242 ms, SD_{d3} = 16 ms; M_{d4} = 244 ms, SD_{d4} = 16 ms; M_{d5} = 243 ms, SD_{d5} = 16 ms). A subsequent test examining saccadic latencies (across all distractor types) as a function of the saccade destination revealed saccades to distractors (*M* = 221 ms; *SD* = 15 ms) to be significantly faster than saccades to targets (*M* = 245 ms, *SD* = 19 ms), t (7) = -8.41, $p < .001$.[13]

DISCUSSION

Overall, the present results show that saccadic target selection can be influenced by top-down control. Most importantly, this does not only hold true for an overall analysis of saccadic latencies, but also for the 25 percent shortest 'early' saccades. We examined three different possible indicators for top-down control: (a) the distribution of target and distractor fixations for comparable target and distractor salience; (b) the salience difference at which there is an equal selection probability for target and distractor; and (c) whether or not there are negative salience differences for which there are more target than distractor fixations.

As expected based on previous findings (e.g., Siebold, van Zoest, & Donk, 2011; van Zoest & Donk, 2005, 2008), the overall (averaged over time) percentage fixation distributions showed a clear pattern indicative of top-down control. Most importantly, however, all three indicators of top-down control were observable, too, in the percentage fixation distribution for the 25% shortest saccadic latencies: When target and distractor were of comparable salience, the majority of saccades went to the target. The (estimated) salience difference at which the selection of the target and distractor was equally likely (50% : 50%) was clearly negative, that is, the distractor had to be much more salient than the target to be selected with equal probability. For the 25% shortest saccadic latencies, the point of equal selection probability (estimated by linear interpolation on the averaged data) was a salience difference of -38 ms. This means that top-down control was strong enough for the target to overcome a bottom-up salience advantage of the distractor as large as a 38-ms detection time difference. Restated, in terms of detection time, the distractor would have to lead the target by 38 ms in order to attract 50% of first saccades. This provides a strong quantitative indicator of top-down control. Finally, there were distractors more salient than the target, which were selected significantly less often than the target. The fact that those three observations were made not only for the overall percentage fixation distribution, but also for

[13] Some observers made very few distractor fixations, especially with distractors number 4 and 5; hence, it was not possible to reliably examine for interaction effects between distractor salience and saccade destination. Also, note that the present paradigm does not allow for the estimation of a latency interference value (i.e., $\text{latency}_{\text{distractor-present}} - \text{latency}_{\text{distractor-absent}}$), as there were no distractor-absent trials.

the percentage fixation distribution of the 25% shortest saccadic latencies, demonstrates that early saccadic selection, too, can be subject to top-down control to a certain degree.

This is in line with Guided-Search-type models (e.g., Müller, Heller, & Ziegler, 1995; Wolfe, 1994; see also Zehetleitner, Proulx, & Müller, 2009), which assume a top-down modulation of bottom-up salience signals at preattentive levels: Accordingly, even early attentional deployments should be subject to the observer's goals (e.g., ignoring an irrelevant singleton). These findings are also in line with reports by Nordfang, Dyrholm, and Bundesen (2013), who recently introduced a new irrelevant-singleton paradigm to disentangle the effects of feature contrast and relevance in initial attentional selection. They reported main effects of both contrast and relevance, and an interaction between these effects. Crucially, they used brief stimulus exposures; hence, excluding the possibility that their relevance effects stem from later stages of processing. In line with the present results, this demonstrates that early top-down control is possible.

The present results provide also support for the *timing account* of visual selection (e.g., van Zoest et al., 2004), according to which stimulus-driven and goal-driven processes operate in different time windows: Our results confirm that the contribution of top-down control increases over time (i.e., as saccadic latencies grow larger). For instance, comparing the percentage distribution for the four temporal trial bins shows that the estimated point of equal selection probability moves to a more negative salience difference as saccadic latencies increase (see Figure 5): the respective intersection points in Figure 5 (estimated by linear interpolation on the averaged data) are -38 ms for the first 25% trial bin, -43 ms for the second bin, and -52 ms for the third bin. In line with previous findings (e.g., Siebold, van Zoest, & Donk, 2011; van Zoest & Donk, 2005, 2008), the longest saccadic latencies were hardly affected by the bottom-up salience of the distractor.

The present findings are at variance with a categorical difference in control operations between early and later time windows: Our results demonstrate that even early top-down control can be powerful enough to overrule bottom-up salience-based signaling. Thus, instead of a categorical model, this argues in favor of a continuum model of goal-driven control (see also van Zoest & Donk, 2008), where the top-down influence on (saccadic target) selection increases gradually over time – importantly, however, with the influence on early selection being actually much stronger than originally envisaged. The latter is evidenced by our quantitative indicator of top-down control: even for the 25% shortest saccadic latencies, top-down control can raise the selection salience of the target to that of a (hypothetical) distractor with a (bottom-up) selection advantage of 38 ms. While this value, indicative of the strength of top-down control, increased with processing time (e.g., in the second 25% trial bin, top-down control was strong enough to compensate for a 43 ms distractor advantage), the increase appeared rather small compared to the already very substantial top-down influence for the first 25% trial bin. This strongly argues that early top-down control over saccadic target selection is not that limited after all.

Note that even though saccadic target selection can be taken as a reliable indicator of covert attentional deployment, since the programming of a saccade seems to obligatorily involve a covert shift of attention to the saccade target (Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995), claims about covert visual attention based on an overt visual attention task should be made with caution: This is because a covert shift of attention is not necessarily accompanied by a saccade. For instance, in the present paradigm, it would, in principle, be possible that covert visual attention initially went to the irrelevant distractor, was then disengaged from there and only subsequently directed to the target item to which a saccadic eye movement was eventually made.

Comparison to previous results

In the present study, for quantifying the amount of top-down control applied, we estimated the (salience difference) point of equal selection probability for the target and distractor. This can be regarded as an alternative to the ‘difference scores’ procedure proposed by van Zoest and Donk (2008), in which the identities of the target and distractor are switched across conditions to determine how many more saccades go to a singleton when it is defined as a target versus a distractor. Our results demonstrate that when target and distractor are of comparable salience, the target has a very substantial selection benefit over the distractor – even relatively early in the selection process. This is in line with some of van Zoest and Donk’s (2008) data (in their Experiments 1 and 3), where even short-latency saccades went to a singleton significantly more often when it was a target compared to when it was a distractor – at least when target and distractor were dissimilar.

However, our finding that a target has a huge selection benefit over an equally salient distractor stands in contrast to other previous reports: Van Zoest et al. (2004, Experiment 1; see also their Experiment 4), using equally salient orientation targets and distractors (i.e., tilted 45° to the left or to the right), observed initial selection performance at chance level. There are several possible reasons for these divergent result patterns. For instance, in the present experiment, target and distractor were defined in different dimensions (i.e., orientation and color), whereas van Zoest et al. (2004) presented targets and distractors defined in the same dimension. Recent evidence suggests that it is easier to down-modulate capture by cross-dimensional distractors than by intra-dimensional distractors (Zehetleitner, Goschy, & Müller, 2012; see also Treisman, 1988). This has been interpreted in terms of a dimensional, or 'hierarchical', weighting structure (e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Müller, Reimann, & Krummenacher, 2003; Müller et al., 2010): with intra-dimensional distractors, an increased weighting of the target feature – which is assumed to benefit the whole respective feature dimension – will bring along weighting benefits for the distractor feature, too, making it more difficult to down-modulate capture by intra-dimensional, compared to cross-dimensional, distractors. For instance, imagine looking for someone wearing a pink jacket at the train station. On the dimension-weighting account, you would focus on 'pink', which would bring about an increased benefit for all color-defined feature singletons (compared to singletons defined in other feature dimensions); accordingly, it would be difficult to prevent attentional capture by someone wearing a yellow jacket. This processing difference between intra- and cross-dimensional distractors might explain why, in the present experiment, the target had a large benefit over equally salient (cross-dimensional) distractors, while previous experiments reported no such benefit of the target over equally salient (intra-dimensional) distractors.

A, in some sense, similar suggestion has been put forward by van Zoest and Donk (2008), who did observe evidence for early top-down control (even with intra-dimensional distractors), but only when target and distractor were dissimilar ('red' and 'green'), rather than being similar ('orange' and 'pink'). Accordingly, to them, the critical factor for the possibility of early top-down control is not intra- vs. cross-dimensionality, but target-distractor similarity. This could also account for the differences between the present results and previous findings: In the present experiment (where we observed an early target benefit over an equally salient distractor), target and distractor were rather dissimilar (by virtue of being defined in different, orientation and color, dimensions), whereas in previous experiments (where initial selection with equally salient distractors was at chance level) target and distractor were more similar (both defined by the same degree of orientation: 45° vs. -45°).

Furthermore, it is also possible that we observed a higher degree of top-down modulations compared to previous studies because our observers had a particularly high incentive to operate top-down control. For instance, a growing body of research demonstrates that distractor interference (i.e., manual RT slowing in the presence vs. the absence of a singleton distractor) varies in magnitude as a function of overall distractor prevalence, with relatively little interference when distractors are frequent and pronounced interference when distractors are rare (high and, respectively, low suppression incentive; e.g., Forster & Lavie, 2008; Geyer, Müller, & Krummenacher, 2008; Müller et al., 2009; Zehetleitner, Proulx, & Müller, 2009). In the present experiment, distractors were present on every trial, that is, participants would have had a particularly large incentive for distractor suppression. Note, however, that using an equally salient, intra-dimensional distractor, van Zoest et al. (2004, Experiment 4) observed chance level initial selection despite presenting a distractor on every trial.

Finally, the present experiment presented observers with two distractors of comparable salience and three more salient distractors. Arguably, the (overall) incentive for top-down control in such a condition is higher compared to a condition in which there is only one distractor of comparable salience.

Relatively long saccadic latencies

For interpreting the relatively large top-down influences observed in the present study, it may also be important to take into account the fact that our short-latency saccades ranged from around 190 ms to 210 ms – which is clearly slower compared to most previous studies (latencies ranging from around 150 ms to 180 ms; e.g., van Zoest, Donk, & Theeuwes, 2004, and van Zoest & Donk, 2008). This leaves the possibility that we might have observed stronger stimulus- (and weaker, if any, goal-) driven influences had our short saccade latencies been in a faster range. For instance, recent evidence suggests that the influence of salience starts to decay with latencies above 180 ms (Markowitz, Shewcraft, Wong, & Pesaran, 2011; Schütz, Trommershäser, & Gegenfurtner, 2012). It is, however, also possible that goal-driven effects in the present paradigm were not stronger compared to previous investigations, but rather that they were simply better observable: It has been argued (e.g., Zehetleitner, Krummenacher, Geyer, Hegenloh, & Müller, 2011) that with highly salient items, salience approaches a saturation asymptote (e.g., Gao, Mahadevan, & Vasconcelos, 2008), which allows for only minimal (if any) additional modulations of top-down control. By contrast, with less salient items, such top-down effects should become more readily observable. Accordingly, it is possible that we observed particularly large top-down modulations because the absolute salience values of the relevant items were comparably low (which might have caused slower decision times, i.e., saccadic latencies). With higher absolute salience values of the relevant items (i.e., with faster decision times), it is therefore possible that the same amount of top-down control would yield smaller observable modulations.

Note, however, that there are also reports, based on a similar paradigm, of much slower saccades that showed no indication of any top-down control whatsoever. For instance, van Zoest et al. (2004) did not report any top-down influences for latencies up to 250 ms (Experiment 2) or even up to 300 ms (Experiment 1). However, though, they used targets and distracters both defined by orientation and, hence, within the same dimension; this may not be directly comparable to the present manipulation. Note also that we observed a very distinct effect of salience difference in our first 25% bin of (short-latency saccade) trials, that is: the more a distractor differed in salience from the target, the more saccades were attracted by the distractor. This marked effect of stimulus salience is at variance with arguments that stimulus-driven influences had already dissipated by this time. In view of this, it is rather unlikely that the present results are simply attributable to our short-latency saccades having been too slow for stimulus-driven control to remain dominant.

On the other hand, it is quite possible that the saccadic latencies in our paradigm were relatively longer because the target was defined by a relatively smaller feature contrast to the nontarget surround, compared to previous studies: we used a bar tilted 12° to the left or the right relative to vertical nontargets, while van Zoest et al. (2004), for instance, used an orientation difference of 45°. That local feature contrast has an effect on attentional selection has recently been demonstrated by, for example, Töllner, Zehetleitner, Gramann, and Müller (2011): they observed a salience-dependent modulation of both the latency and amplitude of the N2pc component in a pop-out search task, which is assumed to reflect the allocation of focal attention in visual space (e.g., Eimer, 1996; Luck & Hillyard, 1994). Accordingly, local feature contrast determines the time it takes for attention to be deployed to the target item, even for singletons detectable via 'efficient' search (see footnote 3). This phenomenon of pop-out speed can also be observed in the present study: the manipulation of color contrast in the go/no-go experiment lead to a difference of ca. 60 ms between high and low contrast color targets. For orientation, similar latency differences have been reported for reaction times (Zehetleitner, Krummenacher, & Müller, 2009; Zehetleitner, Krummenacher, et al., 2011) or the initiation latencies of pointing movements (Zehetleitner, Hegenloh, & Müller, 2011). Thus, the latency difference between saccades in the present and previous studies could reflect slower speed of pop-out due to the 12° target contrast. Also note that in the present experiment, there were twelve possible target positions, while previous studies (e.g., van Zoest et al., 2004; van Zoest & Donk, 2008) used only six different positions.

Accordingly, in the present experiment, there were fewer target position repetitions. Given that target position repetitions can increase the speed of pop-out (e.g., Maljkovic & Nakayama, 1996; Krummenacher, Müller, Zehetleitner, & Geyer, 2009), it is possible that we observed longer saccadic latencies due to our design involving fewer target position repetitions.

Salience estimation procedure

It is important to note that the present interpretations and conclusions rely on the soundness of the salience measurement. As the relative salience between two items defined in two different feature dimensions cannot be determined with certainty, the current approach should be regarded as a salience estimation procedure. This procedure was recently introduced by Zehetleitner et al. (2013) and follows common reasoning in taking target detection RTs as indicative (i.e., estimates) of the targets' respective salience values (e.g., Theeuwes, 1992). Although salience estimates might turn out differently depending on whether a singleton is presented alone (as was the case in the present salience measurement experiment) or presented together with an additional singleton (as was the case in the present eye tracking experiment), in the present study, this would have affected the saliences estimated for the target and the distractors to the same degree, thus leaving the relative salience estimates unaffected. It is also possible that the detection RTs measured in the salience 'estimation' experiment do not exclusively reflect the bottom-up salience values of the target and distractor features. For instance, the detection RTs could in part also be influenced by a top-down attentional set for the respective feature category: as orientation and color features were presented in different blocks, observers might have formed an attentional set for the (in a given block) relevant feature dimension. However, again, this should have affected the estimated target and distractor saliences to a similar degree, hence not affecting the relative salience estimates. Finally, note that the present salience estimation was based on a visual search task, whereas the (subsequent) task in which we analyzed for top-down influences was a saccadic selection task. This relies on the assumption that a single, motor-unspecific salience map guides covert attention as well as overt eye and hand movements (e.g., Zehetleitner, Hegenloh, et al., 2011); that is, the salience representation is identical for the visual search and saccadic selection tasks. However, it is also possible that the planning of an eye movement has a special influence on the computation of the salience map. This is plausible given that planning particular actions, such as manual pointing versus grasping movements, has been found to modulate the weighting of early visual (dimensional) processing and selective attention mechanisms (Wykowska, Schubö, &

Hommel, 2009; see also Wykowska & Schubö, 2012). Similarly, with regard to oculomotor planning, processes of target selection for producing smooth pursuit versus saccadic eye movements are likely to involve differential weighting of information from different feature dimensions (Spering, Montagnini, & Gegenfurtner, 2008).

If indeed the task demands of manual detection and saccadic selection or other factors indicated above would influence the relative salience measure, both the salience of color and that of orientation can be independently become greater or smaller for the saccadic compared to the manual task. Let S_O^{man} and S_C^{man} denote the levels of orientation (O) and color (C) salience effective in the manual RT task (man), and S_O^{sel} and S_C^{sel} the saliences effective in the selection task (sel). It is generally agreed that salience is inversely proportional to RTs: $S^{man} \sim 1/RT^{man}$: the higher a target's salience, the faster the corresponding manual RT. Assume that effective salience in the selection task differs from that in the manual task by an amount denoted by Δ_O and Δ_C independently for both dimensions: $S_O^{sel} = S_O^{man} + \Delta_O$ and $S_C^{sel} = S_C^{man} + \Delta_C$. Thus, $\Delta_{C/O}$ stands for the estimation error when using manual RTs to estimate selection salience: a positive delta value denotes that the manual RT task underestimates ocular selection salience. As outlined above, such estimation errors could potentially derive from motor dimension weighting or top-down effects due to differences in the manual vs. ocular selection task. This formulation allows posing the question more formally, under what conditions it is justified to estimate S^{sel} from manual RTs. Crucially, absolute salience values are mostly irrelevant, as we are interested in salience differences. The relative salience difference is usually estimated by calculating the difference in detection RTs (a standard procedure, see e.g., Theeuwes, 1992): $RT_C^{man} - RT_O^{man} \sim S_O^{man} - S_C^{man}$. Remember, this RT difference is used to quantify salience difference between targets and distractors in the present study and is for instance depicted as the x-axes in Figures 4 and 5. For example, if color RT is 50 ms faster than orientation RT, resulting in a negative RT difference, the color target is more salient than the orientation target. Additionally, greater RT differences indicate greater differences in salience. Now, the salience difference responsible for attentional capture in the selection task can be expressed in terms of salience effective in the manual task: $S_O^{sel} - S_C^{sel} = S_O^{man} - S_C^{man} + (\Delta_O - \Delta_C)$. That is, how much does the salience difference between target and distractor in the selection task (left hand of the equation) differ from the salience difference in the manual task?

Consequently, there are three different types of estimation errors that can be made when estimating selection salience from manual RTs: First, some factor of influence (e.g., top-down control) could affect salience in the manual task by an equivalent amount in both dimensions ($\Delta_O = \Delta_C$). This case is unproblematic, since the estimated salience difference directly reflects the difference effective for capture in the selection task. Second, some factor of influence in the manual task could favor orientation more than color ($\Delta_C > \Delta_O$)[14]. Again, this case is unproblematic, since our salience difference estimate from the manual RTs would be rather conservative and the real data curves in our Figures 4 and 5 would be shifted more towards the left. Third, some factor of influence in the manual task could favor color more than orientation ($\Delta_O > \Delta_C$)[15]. This is the only case that could be potentially problematic for our conclusions, since the real data curves in our Figures 4 and 5 would be shifted more towards the right. However, this would only be problematic if color salience would be considerably overestimated relative to orientation salience ($\Delta_O \gg \Delta_C$), namely so much that the estimated point of equal selection probability would be located at zero (or even above zero).

Possible contributions of intertrial priming

The present experiment was designed to assess the relative contributions of bottom-up salience difference and top-down control to the allocation of attention in visual search. There is a growing consensus (e.g., Awh, Belopolsky, & Theeuwes, 2012; Müller et al., 2010) that a strict bottom-up versus top-down dichotomy does not hold, as there are additional contributing factors. Prominent among those is the selection history, that is: inter-trial priming of target or, respectively, distractor features, which has traditionally been interpreted as an automatic, bottom-up process (e.g., Pinto, Olivers, & Theeuwes, 2005). We cannot exclude the possibility of inter-trial priming having contributed to saccadic target selection in the present paradigm. Note, however, that the target in the present experiment was tilted unpredictably to either the left or the right, decreasing target (orientation) repetitions and thus the target's priming advantage compared to similar previous studies in which the target was typically held constant across a block of trials (e.g., van Zoest et al., 2004; van Zoest & Donk, 2008). In addition, the distractor features switched unpredictably from one trial to the next (one of five alternative colors). Previous research has indicated that a relatively rare (i.e., relatively unpredictable) distractor leads to increased distractor interference compared

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[14] $\Delta_C > \Delta_O$, i.e. the manual RT task underestimates S_C^{sel} more strongly than S_O^{sel}; or the manual RT task overestimates S_O^{sel} more strongly than S_C^{sel}; or the manual RT task underestimates S_C^{sel} and overestimates S_O^{sel}.

[15] $\Delta_O > \Delta_C$; i.e. the manual RT task underestimates S_O^{sel} more strongly than S_C^{sel}; or the manual RT task overestimates S_C^{sel} more strongly than S_O^{sel}; or the manual RT task overestimates S_C^{sel} and underestimates S_O^{sel}.

to a relatively frequent (i.e., relatively predictable) distractor (Müller, Geyer, Zehetleitner, & Krummenacher, 2009). Accordingly, in the present experiment, this would have increased the capturing potential of the color distractors.

CONCLUSION

Based on a systematic manipulation of the salience difference between a target and a (cross-dimensional) distractor and an examination of the short-latency saccades, the present results provide evidence that early saccadic target selection can be top-down controlled, at least to some extent: (i) When target and distractor were of comparable salience, the majority of early saccades went to the target. (ii) Target and distractor were only selected with equal probability by short-latency saccades when the distractor was much more salient than the target; the (negative) salience difference at which both were selected with equal probability provides a quantitative indicator of top-down control. (iii) There were even distractors more salient than the target, which were selected significantly less often by short-latency saccades than the target. In line with a timing account of visual selection (van Zoest et al., 2004), quantitative indicators of top-down control increased in magnitude the longer the saccade latencies were – however, with a substantial degree of top-down control operating already in the shortest latency range. This adds further evidence to the notion that top-down control over saccadic target selection is defined on a continuum (van Zoest & Donk, 2008), already early in selection.

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2.3 Probability cueing of distractor locations: Both intertrial facilitation and statistical learning mediate interference reduction

SUMMARY

Previous research has shown that targets in visual search are detected faster if they appear in a probable region of the visual field as compared to a less probable region. This effect has been termed "probability cueing". The third study presented here transferred these findings to distractor shielding, i.e. it was investigated whether probability cueing cannot only facilitate target detection, but can also reduce interference by distractors, which appear in probable regions as compared to distractors, which appear in less probable regions. Experiment 1 demonstrated that this indeed is possible: Distractor interference was considerably reduced if the distractor appeared at a frequent distractor location compared to a rare distractor location. Experiment 2 and 3 were concerned with the question what causes the probability cueing effect for distractor locations. Based on findings from the literature on probability cueing of target locations, "intertrial facilitation" and "statistical learning" were identified as possible contributing factors. Hence, Experiment 2 tested whether intertrial facilitation, i.e. the repetition of distractor positions, irrespective of statistical learning, can lead to reduced distractor interference. It was found that distractor interference was reduced following distractor position repetitions compared to distractor position switches – despite a distractor reappearing at the same position being equally likely as it appearing at any other distractor position. Finally, Experiment 3 tested whether statistical learning, in addition to and irrespective of intertrial facilitation, also contributes to the probability cueing effect for distractor locations. Despite distractor position repetitions being restricted by the design of Experiment 3, reduced distractor interference at frequent distractor locations compared to rare distractor locations, was observed. Taken together, the results of the third study presented in this dissertation demonstrate that probability cueing of distractor locations can drive the shielding of likely distractor locations and that both intertrial facilitation and statistical learning contribute to this effect.

CONTRIBUTIONS

Experiment 1 was carried out in the context of an undergraduate practical course on empirical psychology, which was taught by **HG**: **HG** conceived and designed Experiment 1; the between-subjects factor distractor frequency distribution (left/right vs. top/bottom) was incorporated following student suggestions. Data for Experiment 1 was collected by students of the aforementioned course. **HG** analyzed the data for Experiment 1 and discussed the results with the students. Parts of the experimental work for this study were done in the context of the bachelor thesis project of SB, which was supervised by **HG**. **HG** and SB conceived and designed Experiments 2 and 3. SB collected data for Experiment 2; SB and **HG** collected data for Experiment 3. **HG** and SB analyzed the data for Experiments 2 and 3, and discussed the results. **HG** discussed the results with MZ and HJM. **HG** wrote the paper. MZ and HJM commented on and revised the paper.

REFERENCE

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Probability cueing of distractor locations:

Both intertrial facilitation and statistical learning mediate interference reduction

Harriet Goschy

Ludwig-Maximilians-Universität München, Munich, Germany,

and Graduate School of Systemic Neurosciences, Planegg-Martinsried, Germany

Sarolta Bakos

Ludwig-Maximilians-Universität München, Munich, Germany

Hermann J. Müller

Ludwig-Maximilians-Universität München, Munich, Germany,

and Birkbeck College, University of London, London, UK

Michael Zehetleitner

Ludwig-Maximilians-Universität München, Munich, Germany

ABSTRACT

Targets in a visual search task are detected faster if they appear in a probable target region as compared to a less probable target region, an effect which has been termed "probability cueing". The present study investigated whether probability cueing cannot only speed up target detection, but also minimize distraction by distractors in probable distractor regions as compared to distractors in less probable distractor regions. To this end, three visual search experiments with a salient, but task-irrelevant, distractor ("additional singleton") were conducted. Experiment 1 demonstrated that observers can utilize uneven spatial distractor distributions to selectively reduce interference by distractors in frequent distractor regions as compared to distractors in rare distractor regions. Experiment 2 and 3 showed that intertrial facilitation, i.e. distractor position repetitions, and statistical learning (independent of distractor position repetitions) both contribute to the probability cueing effect for distractor locations. Taken together, the present results demonstrate that probability cueing of distractor locations has the potential to serve as a strong attentional cue for the shielding of likely distractor locations.

INTRODUCTION

In our daily visual environment, objects tend to be unevenly distributed, i.e. they are more likely to appear in certain regions and less likely to appear in other regions. Previous research has demonstrated that observers can take advantage of uneven distributions of object positions, so as to more quickly detect or discriminate objects at probable, as compared to less probable, locations (e.g., Druker & Anderson, 2010; Fecteau, Korjoukov, & Roelfsema, 2009; Geng & Behrmann, 2002, 2005; M. L. Shaw & Shaw, 1977). There is some evidence (Reder, Weber, Shang, & Vanyukov, 2003) suggesting that observers can likewise take advantage of uneven distributions of distracting objects, to minimize interference by distractors at probable, as compared to less probable, locations. The present study was designed to examine probability cueing of distractor locations in more detail, in particular: In visual search, is interference by distractors at frequent locations reduced because it is easier to ignore a distractor at a (just) recently ignored location ("intertrial facilitation")? Or do observers acquire strategies to shield against interference from certain locations based on the probability of a distractor appearing there ("statistical learning")?

The finding that observers can exploit uneven distributions of target locations to enhance search performance has been referred to as "location probability effect" (Miller, 1988) or "probability cueing effect" (Geng & Behrmann, 2002). The earliest reports go back to M. L. Shaw and P. Shaw (1977), who asked their observers to recognize a target letter which appeared with varying probabilities (25% vs. 10% vs. 5%) at different locations of the display. Recognition accuracy for the target letter was better at locations with a higher probability of containing the target (for similar reaction time data, see M. L. Shaw, 1978; see also Müller & Findlay, 1987). Miller (1988) observed probability cueing effects for both absolute spatial locations (i.e., screen positions) and relative spatial locations (i.e., positions within a configuration of items). While Miller (1988) reported these two modulations to be of similar magnitude, Hoffmann and Kunde (1999) argued that probability cueing effects are more strongly driven by relative, as compared to absolute, spatial locations (see also Chun & Jiang, 1998). In a visual search task, Geng and Behrmann (2002) asked their participants to discriminate (the identity of) a target letter presented among several nontarget letters. The target appeared with 80% probability in one half of the display and with 20% probability in the other half. Participants were not explicitly instructed about this uneven distribution, and the majority did not report any awareness of it at the end of the experiment. Nevertheless, response times (RTs) were reduced for targets appearing in the more probable, as compared to the less probable, target region.

Although probability cueing effects of this kind have since been reported repeatedly within a variety of paradigms (e.g., Druker & Anderson, 2010; Fecteau et al., 2009; Geng & Behrmann, 2005), the mechanisms underlying the probability cueing effect are still subject to debate. Traditionally, probability cueing effects have been interpreted in terms of statistical learning, that is, the formation of location-specific stimulus expectancies that reflect the statistical likelihood of a target appearing at a specific location (or region) across a longer sequence of trials (e.g., Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Hoffmann & Kunde, 1999). However, examinations of statistical learning in probability cueing paradigms have typically been confounded by short-term intertrial effects: if a target is more likely to appear at a particular location, the probability of cross-trial target repetition(s) at that location is also increased, facilitating performance. In fact, a host of studies have shown that repeating the target position on consecutive trials yields improved performance compared to positional changes (e.g., Geyer, Zehetleitner, & Müller, 2010; Kristjánsson, Vuilleumier, Schwartz, Macaluso, & Driver, 2007; Kumada & Humphreys, 2002; Maljkovic & Nakayama, 1996). Walthew and Gilchrist (2006) have argued that target position repetitions of this kind, as opposed to statistical learning, are the underlying mechanism of the probability cueing effect. In their experiment, the target was more likely to appear on one side of the display compared to the other. In addition, there were two (between-subjects) repetition conditions: For the “repeat” group, target position repetitions were not restricted; for the “non-repeat” group, by contrast, there were no repetitions of the target position within a sequence of four trials. A probability cueing effect was observed only for the repeat group, but not for the non-repeat group; that is, when target position repetitions were restricted, there was no “statistical learning” effect (but see Druker & Anderson, 2010, and Jones & Kaschak, 2012). Note that statistical learning and intertrial facilitation as underlying mechanisms of the probability cueing effect are not necessarily mutually exclusive: for instance, recent work by Kabata and Matsumoto (2012) suggests that both statistical learning and intertrial facilitation contribute to the probability cueing effect, but that learning the target location probability is mediated by target location repetitions on consecutive trials.

There are reasons to assume that search performance is influenced not only by statistical properties of the target, but also by statistical properties of possible distracting stimuli. For instance, interference by salient but irrelevant distractors (i.e., RT slowing in the presence compared to absence of a distractor) varies in magnitude as a function of distractor prevalence, with relatively little interference when distractors are frequent and substantial interference when distractors are rare (Forster & Lavie, 2008; Geyer, Müller, & Krummenacher, 2008; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Sayim, Grubert, Herzog, & Krummenacher, 2010; Zehetleitner, Krummenacher, & Müller, 2009). Reder et al. (2003) investigated probability cueing of distractor positions in a target localization task. In their experiments, observers had to indicate which of four locations contained a target item (“o”), while a distractor item (“x”) could be present at the same time at one of the other locations. Critically, the distractor was not equally probable at those locations, which influenced RT performance: while distractors at frequent locations caused essentially no RT interference, distractors at rare locations produced considerable RT slowing. Importantly, Reder et al. did not specifically examine the mechanism(s) underlying probability cueing. Hence, their design does not exclude the possibility of short-term facilitation, arising from distractor position repetitions, being the critical factor; in fact, as there were only four possible display locations (at which distractors occurred with unequal probabilities), distractor position repetitions would have been rather frequent.

The main goal of the present study was to examine what causes the probability cueing effect for distractor locations: statistical learning, intertrial facilitation, or both. Unlike Reder et al. (2003), who used a target localization task with prime and probe displays, we employed a more classical visual search task in which observers had to search for a target item surrounded by several nontargets. In a certain proportion of the trials, a task-irrelevant but salient distractor was presented ("additional-singleton paradigm"; Theeuwes, 1992), and distraction was operationalized as RT interference in the presence versus the absence of this distractor. To our knowledge, probability cueing of distractor locations has hitherto only been investigated by Reder and colleagues in a non-classical visual task, and there has never been a formal investigation of whether the probability cueing effect for distractor locations is due to intertrial facilitation or statistical learning or both. In other words, is interference by distractors in frequent locations reduced (compared to distractors in rare locations) because it is easier to ignore a distractor at a just recently ignored location? Or do observers acquire strategies of shielding processing from interference signals arising at certain locations based on the probability of a distractor appearing there? Or do both intertrial facilitation and statistical learning contribute to the effect?

To resolve this question, Experiment 1 was designed to, first of all, demonstrate probability cueing of distractor locations in a classical visual search paradigm, that is: would distractors at frequent locations cause less interference (i.e., RT slowing) than distractors at rare locations? Experiment 2 investigated the contribution of intertrial facilitation (i.e., distractor position repetitions) to interference reduction, that is: is it easier to ignore a distractor appearing at location that had just recently contained a distractor? Finally, Experiment 3 was designed to examine whether distractor position repetitions are a prerequisite for the probability cueing effect for distractor locations, that is: would statistical learning also occur if distractor position repetitions are excluded by the experimental design?

EXPERIMENT 1

Experiment 1 was designed to examine whether probability cueing of distractor locations can be used to selectively down-modulate interference by salient but irrelevant distractors (i.e., RT slowing on distractor-present, as compared to distractor-absent, trials) in a classical visual search task with orientation-defined targets and colour-defined distractors. If this were the case, distractors at frequent distractor locations should cause less interference compared to distractors at rare distractor locations. Note that Experiment 1 was not yet meant to address the mechanism underlying this (possible) interference reduction (statistical learning, intertrial facilitation, or both), but rather to simply demonstrate the general effect in the present paradigm.

In contrast to Reder et al. (2003), who demonstrated a probability cueing effect on distractor interference in a target localization paradigm, we used frequent and rare distractor areas instead of single (absolute) distractor positions with different probabilities: if present (50% of the trials), the distractor appeared with a probability of 90% at one of the positions within the frequent distractor area, and with a probability of 10% at one of the positions within the rare distractor area. The target, which was present on every trial, appeared with equal probability in both distractor areas. The frequent versus rare distractor area was either the left versus the right hemifield, or, for a different group of observers, the bottom versus the top hemifield. Distractor position repetitions were not restricted by the experimental design.

Method

Participants. Twenty-five (19 female, 23 right-handed) observers with a median age of 22 years (range: 19-42 years) participated in this experiment. All of them reported normal or corrected-to-normal visual acuity and colour vision. They were randomly assigned to the left/right group (n = 13) or the top/bottom group (n = 12).

Stimuli. The stimulus display, presented on a black background, consisted of grey (RGB: 127, 127, 127; CIE [Yxy]: 13.6, .28, .32) vertical bars (0.25° of visual angle wide, 1.35° high) whose geometric centres were equidistantly arranged on the circumferences of three concentric (imaginary) circles, with radii of 2°, 4°, and 6° and encompassing 6, 12, and 18 bars, respectively; a further grey bar occupied the position in the centre of the three circles. In every bar, there was a gap 0.25° in height, which was randomly located 0.25° from the top or the bottom of the bar. The target differed from the nontargets by its orientation: In a random half of the trials, it was tilted 12° to the left, in the other half 12° to the right. If a distractor was present, one of the nontargets was red (RGB: 252, 0, 21; CIE [Yxy]: 14.2, .62, .34). The target and, if present, the distractor could appear only on the middle circle.

Apparatus. The experiment was conducted in in a sound-isolated, dimly-lit cabin with black interior. The search displays were presented on a monitor (22-inch Mitsubishi Diamond Pro® 2070SB, refresh rate of 120 Hz, resolution of 1,024 x 768 pixels), which observers viewed from a distance of about 70 cm. Stimuli were generated using a ViSaGe system (Cambridge Research Ltd., UK) and the Experimental Toolbox (Reutter & Zehetleitner, 2012) for MATLAB® (The MathWorks®, Inc.), controlled by a personal computer running under the Windows XP® operating system. The observers were asked to report whether the target bar had a gap at the top or the bottom by pressing the “Z” or the

“M” key of a QWERTY keyboard (Empirisoft DirectIN, Empirirsoft Corporation, USA) using the index finger of their left and right hands, respectively.

Design. The experiment consisted of 800 trials presented in 8 blocks of 100 trials. Distractors were present in a random half of the trials (50 trials per block). The frequency distribution of the distractors was introduced as a between-subjects factor. For the left/right group, the frequent versus rare distractor area was the left vs. right hemifield, that is, the range from the 7 o’clock to the 11 o’clock position versus the 1 o’clock to the 5 o’clock position on the middle display circle (see Figure 1). For the top/bottom group the frequent versus rare area was the top versus the bottom hemifield, that is, the range from the 10 o’clock to the 2 o’clock position versus the 4 o’clock to the 8 o’clock position (see Figure 1). In the left/right group, neither the target and nor distractor ever appeared at the 12 o’clock and 6 o’clock positions, as these positions could not be assigned to either the left or right hemifield (i.e., the frequent or rare area), respectively. The same was the case for the top/bottom group and the 3 o’clock and 9 o’clock positions. The assignment of frequent and rare areas to left and right hemifields (or to top and bottom hemifields, respectively) was counterbalanced between participants.

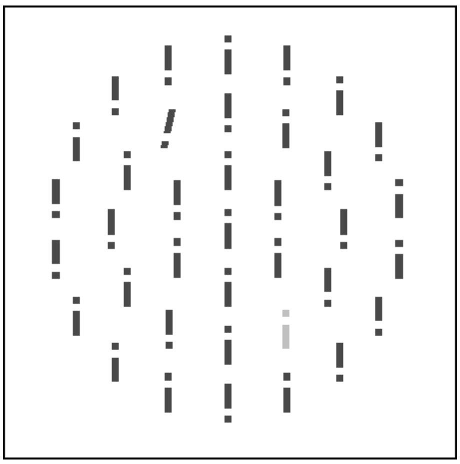

Figure 1. Illustration of a stimulus display: The target item was defined by orientation and tilted 12° to the left or to the right. The distractor was defined by colour: If a distractor was present, one of the nontarget items was red (light-grey in the example). The observers’ task was to indicate whether the target bar had a gap at the top or at the bottom.

If a distractor was present, it appeared with 90% probability in the frequent hemifield and with 10% probability in the rare hemifield. Of the 50 distractor trials per block, there were 45 trials with a distractor in the frequent area (nine per frequent distractor position) and five with a distractor in the rare area (one per rare distractor position). The target appeared equally often in both hemifields, with an equal probability for all ten possible positions.

However, it never co-occurred with the distractor on one position, that is, there was never a red tilted bar. Trial presentation order within the blocks was randomized.

Procedure. Prior to the experiment, all observers received both written and oral instructions: Their task was to indicate whether the target bar had a gap at the top or at the bottom and to proceed as fast and yet as accurately as possible. They were informed that on some trials, one of the nontargets would be red, which would be irrelevant to their task. However, they were not informed about the manipulation of distractor location probability. Each trial started with the presentation of a white fixation cross (0.5° x 0.5°) in the centre of the screen for a random duration between 700 and 1100 ms. Thereupon the search display appeared and remained visible until the observer's key press response. If the response was correct, a new trial began; if the response was incorrect, the word "Fehler" (German for error) was presented in the centre of the screen for 500 ms before a new trial started. After each block of trials, observers were informed about their average reaction time (RT) and their percentage error rate in the previous block via a message on the screen. Observers could take short breaks between blocks of trials and started each block by a button press.

Results

RTs more than three standard deviations above an observer's mean per distractor presence condition (present vs. absent) and below 200 ms were discarded as outliers (1.83% of all trials). Subsequently, error trials were excluded as well (5.64% of all trials). Mean error rates did not differ significantly depending on whether the distractor was absent (5.55%), or appeared at a rare position (6.85%) or at a frequent position (5.48%), $F(1.19, 28.58) = 2.46$, $MSE = 10.24$, $p = .12$, *ns* (Greenhouse-Geisser-corrected values). Accordingly, a speed-accuracy trade-off influence on the RTs can be ruled out.

The mean RTs per observer and condition were entered into a 2x3-ANOVA with the between-subjects factor distractor frequency distribution (left/right vs. top/bottom) and the within-subjects factor distractor condition (distractor absent, distractor in frequent area, distractor in rare area). As can be seen in Figure 2, the top/bottom group exhibited numerically slower overall RTs ($M = 754$ ms, $SD = 155$) than the left/right group ($M = 706$ ms, $SD = 147$); however, this difference was not significant (non-significant main effect of distractor frequency distribution, $F(1, 23) = 0.56$, $MSE = 71{,}646.69$, $p = .46$, *ns*.). The main effect of distractor condition was significant, $F(1.33, 30.62) = 46.27$, $MSE = 1{,}267.24$, $p < .001$, $\eta_p^2 = .67$ (Greenhouse-Geisser-corrected values), and is evident for both the top/bottom group and the left/right group, as indicated by a non-significant interaction effect between distractor frequency distribution and distractor condition, $F(1.33, 30.62) = 0.06$, $MSE = 1,267.24$, $p = .87$, *ns* (Greenhouse-Geisser-corrected values; see also Figure 2).

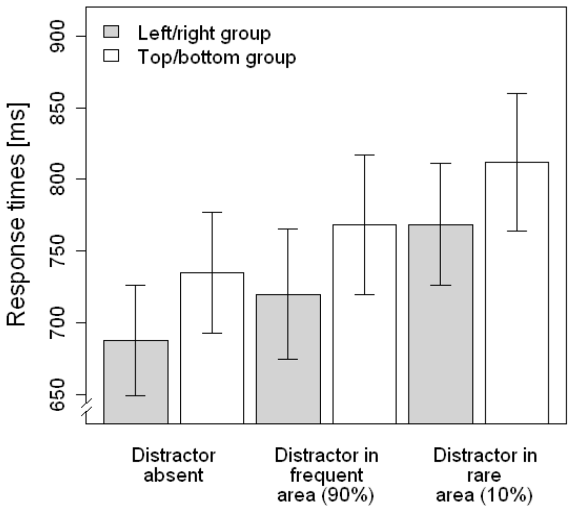

Figure 2. Mean RTs for the top/bottom group and the left/right group dependent on the distractor condition in Experiment 1. Error bars denote one standard error of the mean RT.

As there was no significant interaction effect, we further analyzed the main effect distractor condition, irrespective of the distractor frequency distribution, via planned (orthogonal, one-tailed) t-tests according to our hypotheses. The first comparison tested whether there was a significant overall-interference effect caused by the presence of distractors, by comparing distractor absent RTs to the averaged RTs for the conditions “distractor in frequent area” and “distractor in rare area”. This comparison turned out to be significant, that is, RTs were overall slower when a distractor was present, $t(24) = 7.77$, $p < .001$, $d = 1.55$. The second comparison contrasted the two distractor-present conditions, revealing that RTs were indeed significantly faster if a distractor appeared at a frequent position as compared to a rare position, $t(24) = -5.90$, $p < .001$, $d = 1.18$. As can be seen in Figure 2, the interference caused by a distractor in the frequent area (33 ms) was considerably smaller (though significantly different from zero, $t(24) = 6.27$, $p < .001$, $d = 1.25$) than that produced by a distractor in the rare area (79 ms).

Discussion

In Experiment 1, interference by a salient but irrelevant distractor was reduced if it appeared at a frequent distractor location as compared to a rare location. Hence, the present results demonstrate that probability cueing can not only directly speed up target detection, but can also be used to reduce interference by salient but irrelevant distractors in visual search. In this regard, the present results are in line with Reder et al. (2003), who observed a similar interference modulation in a target localization paradigm. However, unlike Reder et al., we did not manipulate positional distractor probability between single (absolute) distractor positions, but between different distractor areas (i.e., there were several frequent or rare distractor positions). Given this, the present results imply that distractor shielding based on probability cueing of distractor positions, does not only reduce interference for single (precisely defined) distractor positions, but can also extend to larger display areas comprising several distractor positions.

Note that the presently observed effect is not primarily attributable to (cerebral) hemisphere-specific selectivity adaptation, with each hemisphere adopting an appropriate processing strategy independently of the other hemisphere's strategy: we observed no significant interaction between the distractor condition and the distractor frequency distribution (left/right vs. top/bottom). If the observed interference modulation effect were primarily attributable to hemisphere-specific selectivity adjustment, it should have been evident only in the left/right group (in which frequent and rare distractors were presented in different visual hemifields), but not in the top/bottom group (in which both frequent and rare distractors were presented in both hemifields). Hence, the interference modulation observed in Experiment 1 is likely the result of a location-specific selectivity adjustment, and by and large independent of hemisphere-specific processing. In this regard, the present results are in line with a variety of findings in the cognitive control literature, where independent effects of the ratio of congruent and incongruent trials for different stimulus locations were reported that were also not based on hemisphere-specific selectivity (Crump, Gong, & Milliken, 2006; Wendt, Kluwe, & Vietze, 2008; but see also Corballis & Gratton, 2003, for a more hemisphere-specific selectivity account).

The results of Experiment 1 demonstrated that probability cueing of distractor locations enables a selective, location-specific down-modulation of interference by salient but irrelevant distractors. However, Experiment 1 does not permit any conclusions to be drawn about the mechanism(s) underlying this effect: statistical learning, intertrial facilitation, or both. To disentangle these effects, Experiment 2 investigated the contribution of intertrial facilitation independently of statistical learning, while Experiment 3 investigated the contribution of statistical learning independently of intertrial facilitation.

EXPERIMENT 2

Experiment 2 was designed to investigate the contribution of intertrial facilitation (independently of statistical learning) to the probability cueing effect for distractor locations established in Experiment 1, that is: is it easier to ignore a distractor at a just recently encountered distractor location? In the light of previous studies, there is reason to assume that intertrial facilitation (i.e., repeating the distractor position from trial n-1 to trial n) might have contributed to the reduction of distractor interference observed in Experiment 1. For instance, examining distractor interference in a visual search task, Kumada and Humphreys (2002) found RTs to be slowed if a target on the current trial n appeared at a position occupied by a singleton distractor on the preceding trial n-1, which they interpreted in terms of “negative position priming”. If a position previously occupied by a singleton distractor is inhibited (and if the inhibitory tag persists for a while), this should also affect singleton distractors subsequently appearing at that position, resulting in reduced distractor interference.

Experiment 2 was similar to Experiment 1, except, however, that there was no spatial probability manipulation. Instead, both the target and the distractor appeared equally often at one of six different position of the search display, and RTs were analyzed as a function of the intertrial transitions from trial n-1 to trial n. If there is a contribution of intertrial facilitation, we expected distractor interference to be smaller for distractor position repetitions from trial n-1 to trial n as compared to distractor position switches. In addition, based on previous findings (Müller et al., 2009; Zehetleitner et al., 2009), we expected interference on distractor-present trials (trial n) to be larger following distractor-absent trials (trial n-1) compared to both distractor position repetitions and switches, owing to increased recruitment of attentional control following the (recent) encounter of distraction on the preceding trial (see also Botvinick, Braver, Barch, Carter, & Cohen, 2001).

Method

Experiment 2 was methodologically identical to Experiment 1, with the following exceptions.

Participants. Twelve (10 female, all right-handed) new observers with a median age of 25.5 years (range: 20-40 years) participated in Experiment 2.

Design. The experiment consisted of 720 trials presented in 12 blocks of 60 trials. Distractors were present in a random half of the trials (30 trials per block). To ensure a sufficiently large number of distractor position repetitions, there were only six possible distractor positions: The distractor, if present, appeared equally often at the 1, 3, 5, 7, 9, and 11 o'clock positions of the middle display circle (each five times per block). Likewise, the target appeared only, and equally frequently, at one of these positions (10 trials per block). On the one hand, possible distractor and target positions were restricted to those six positions to ensure a sufficient number of position repetition trials. On the other hand, there is also evidence that distractor inhibition might spread spatially to neighbouring positions (Kumada & Humphreys, 2002). By never presenting the target and (if present) the distractor at directly adjacent positions, we tried to avoid possible confounding influences of such spreading positional inhibition. Also, as previously, the target and distractor could not co-occur at one and the same position. Trial presentation order within the blocks was randomized.

Results

RTs more than three standard deviations above the individual observer's mean per distractor presence condition (present vs. absent) and below 200 ms were discarded as outliers (overall, 1.67% of trials). Subsequently, error trials were excluded from the analysis (4.68% of all trials). For data analysis, the trials were sorted into four categories dependent on distractor presence and distractor position on the previous trial n-1 and distractor presence and distractor position on the current trial n: (1) Distractor absent on trial n (irrespective of distractor presence on trial n-1); (2) distractor present on both trial n and n-1 with a distractor position repetition; (3) distractor present on both trial n and n-1 with a distractor position switch; (4) distractor present on trial n, but absent on trial n-1. The first trial of each block was excluded from the analysis, as it was impossible to assign it to a category. After data filtering, the critical distractor position repetition category – with the fewest trials – included on average 22.5 trials per participant (minimum 16 trials). Mean error rates did not differ significantly depending on the distractor condition, $F(3, 33) = 0.53$, $MSE = 3.62$, $p = .67$, *ns*. Therefore, a speed-accuracy trade-off can be ruled out for the RT data.

As can be seen in Figure 3, in line with our hypotheses, there was effectively zero interference on distractor position repetition trials (-1 ms). By contrast, interference was increased on distractor position switch trials (25 ms), and was even larger for distractor-present trials following distractor-absent trials (38 ms). To statistically examine this pattern, the mean RTs per participant and distractor condition were entered into a repeated-measures ANOVA, which revealed the main effect to be significant, $F(1.51, 16.57) = 5.84$, $MSE = 1{,}539.52$, $p = .018$, $\eta_p^2 = .35$ (Greenhouse-Geisser-corrected values). Again, to test our hypotheses, we conducted planned (orthogonal, one-tailed) t-tests to break down this effect.

The first comparison tested whether the overall-interference effect was significant. To this end, distractor-absent RTs were compared to the averaged RTs for the three distractor-present conditions. Indeed, distractor-present RTs were significantly slower overall than distractor-absent RTs, $t(11) = 2.54$, $p = .014$, $d = 0.73$. The second comparison tested whether RTs for distractor-present trials were significantly slower if trial n-1 was a distractor-absent trial, as compared to a distractor-present trial. To this end, the RTs for the condition "distractor present on trial n but absent on trial n-1" were compared to the averaged RTs for the other two distractor-present conditions ("distractor position repetition" and "distractor position switch" conditions). This comparison revealed a significant difference, $t(11) = 2.52$, $p = .014$, $d = 0.73$. Finally, we tested whether RTs for distractor position repetition trials were significantly faster than RTs for distractor position switch trials, which was the case, $t(11) = 2.22$, $p = .024$, $d = 0.64$.

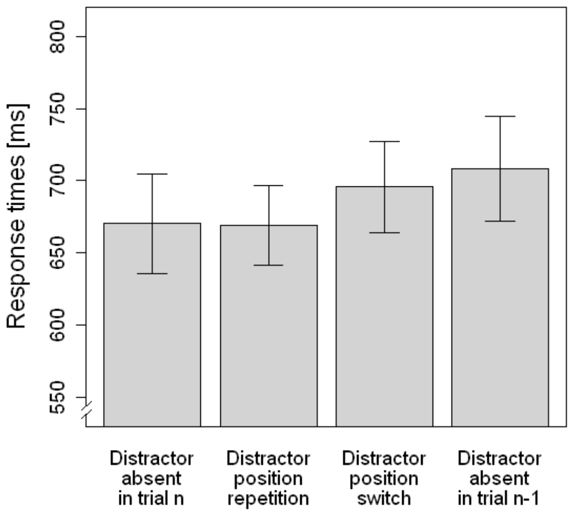

Figure 3. Mean RTs for the four distractor conditions in Experiment 2: Distractor absent in the current trial n, distractor position repetition from the previous trial n-1 to the current trial n, distractor position switch from n-1 to n or distractor absent in trial n-1, but present in n. Error bars denote one standard error of the mean RT.

Discussion

Experiment 2 yielded a significant distractor interference effect (comparison 1), with interference on trial n being significantly reduced if a distractor was present versus absent on trial n-1 (comparison 2). This replicates previous findings (Müller et al., 2009; Zehetleitner et al., 2009) and is in line with the assumption that a conflict encounter (i.e., a distractor-present trial) leads to increased recruitment of cognitive control, which helps to resolve subsequent conflict encounters (Botvinick et al., 2001).

Most importantly, RTs on distractor-present trials following distractor-present trials were significantly faster if the distractor position was repeated rather than switched (comparison 3). Hence, we observed significant intertrial facilitation by distractor position repetitions: observers could more effectively control for distractor interference following distractor position repetitions compared to distractor position switches. In fact, responding on distractor position repetition trials was not slowed at all compared to distractor-absent trials (-1 ms), that is, interference was completely eliminated following a distractor position repetition. It should be emphasized that this was the case despite a distractor re-appearing at the same position was just as likely as it appearing at any other distractor position, that is: there was no specific incentive to shield from interference arising at a recent distractor position.

Taken together, the results of Experiment 2 demonstrate that distractor position repetitions give rise to intertrial facilitation: interference from singleton distractors can be down-regulated more effectively if the position of a distractor repeats from trial n-1 to trial n, as compared to a position switch. As we did not prevent distractor position repetitions in Experiment 1 and the rate of repetitions was higher for the frequent, as compared to the rare, distractor area, the probability cueing effect observed in Experiment 1 is at least partly attributable to intertrial facilitation on distractor position repetitions. Given this, the goal of Experiment 3 was to investigate whether statistical learning – in addition to intertrial facilitation – might have contributed to the probability cueing effect in Experiment 1, or whether this effect was attributable solely to intertrial facilitation.

EXPERIMENT 3

The objective of Experiment 3 was to examine whether statistical learning can be observed also in the absence of facilitation by distractor position repetitions. Accordingly, Experiment 3 was basically a replication of Experiment 1, however, the experimental design prevented distractor position repetitions from trial n-1 to trial n (and from trials preceding trial n-1 if all intervening trials were distractor-absent trials).[16] If the probability cueing effect for distractor

[16] The results of Experiment 2 were analyzed as a function of the distractor condition on trial n-2. Overall, there was no significant difference in RTs between position repetition trials (from trial n-2 to trial n) and position switch trials (from trial n-2 to trial n), $t(11) = -0.34$, $p = .74$, *ns* (two-tailed). However, when only those trials were taken into account on which no distractor had been present on trial n-1, RTs were significantly faster for position repetitions from trial n-2 to trial n (M = 670 ms, SD = 137) than for position switches from trial n-2 to trial n (M = 710 ms, SD = 136), $t(11) = -2.26$, $p = .045$, d = 0.65 (two-tailed). Hence, in our paradigm, intertrial facilitation effects diminish after an intervening distractor-present trial, but may be carried over across intervening distractor-absent trials. Accordingly, in Experiment 3, we not only excluded distractor position repetitions from trial n-1 to trial n, but also from trials preceding trial n-1 if the intervening trials were all distractor-absent trials.

locations is solely attributable to intertrial facilitation, no such effect should manifest under the conditions of Experiment 3. However, if statistical learning contributes to the probability cueing effect, reduced distractor interference should also be observable even without distractor position repetitions (which were eliminated in Experiment 3).

Method

Compared to Experiment 1, only the following methodological changes were made in Experiment 3.

Participants. Twenty (13 female, 19 right-handed) new observers with a median age of 25.5 years (range: 19-46 years) participated in Experiment 3.

Design. The experiment consisted of 720 trials presented in 12 blocks of 60 trials. Distractors were present in a random half of the trials (30 trials per block). Both targets and distractors appeared only on the 1, 3, 5, 7, 9, and 11 o'clock positions of the middle display circle (as in Experiment 2). The target appeared equally often on each of these positions. If a distractor was present, it appeared with 90% probability in the frequent hemifield (27 trials per block, with nine trials per possible position) and with 10% probability in the rare hemifield (3 trials per block, with one trial per possible position). Again, target and distractor never co-occurred on one and the same position. For a random half of the participants, the right hemifield was the frequent hemifield and the left hemifield the rare hemifield, and vice versa for the other half of the participants. The design included the following restriction to exclude the influence of distractor position repetitions: The distractor position never repeated on two successive distractor-present trials – regardless of how many distractor-absent trials intervened between the two distractor-present trials (e.g., if trial n-4 was a distractor-present trial and trials n-3, n-2, and n-1 were distractor-absent trials, a distractor on trial n would not appear at the position of the distractor on trial n-4).

Results and Discussion

RTs more than three standard deviations above the individual observer's mean per distractor presence condition (present vs. absent) and below 200 ms were excluded from the analysis (overall, 2.34% of trials), as were error trials subsequently (4.58% of all trials). Mean error rates did not differ significantly depending on whether a distractor was absent (4.33%) or appeared in the rare hemifield (4.94%) or the frequent hemifield (4.20%), $F(1.14, 21.64) = 0.59$, $MSE = 9.30$, $p = .47$, *ns* (Greenhouse-Geisser-corrected values). Consequently, a speed-accuracy trade-off can be ruled out for the RT data.

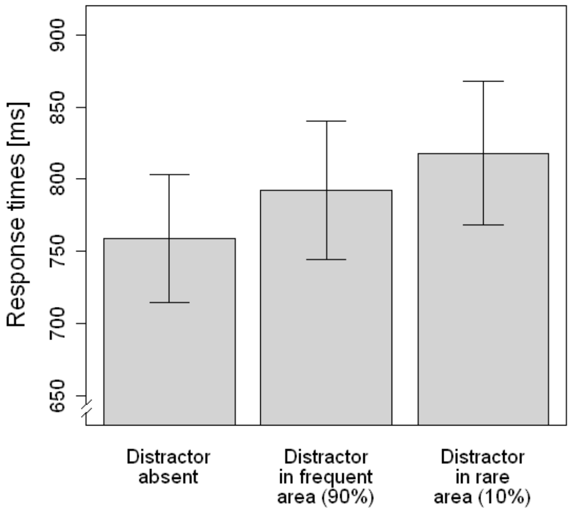

Figure 4. Mean RTs dependent on the distractor condition in Experiment 3. Error bars denote one standard error of the mean RT.

As can be seen in Figure 4, in line with our hypotheses, the interference caused by a distractor in the frequent hemifield (33 ms) was smaller than that caused by a distractor in the rare hemifield (59 ms). To statistically corroborate this observation, the mean RTs per observer and distractor condition (distractor absent, distractor in frequent hemifield, distractor in rare hemifield) were subjected to a repeated-measures ANOVA. This revealed a significant main effect, $F(1.31, 24.87) = 15.16$, $MSE = 1{,}761.21$, $p < .001$, $\eta_p^2 = .44$. Again, this effect was broken down by calculating planned (orthogonal, one-tailed) t-tests according to our hypotheses. The first comparison examined whether the distractors presented caused overall-interference. To this end, distractor-absent RTs were compared to the averaged RTs for distractors in the frequent and rare hemfields. As expected, RTs for distractor-absent trials were significantly faster compared to the mean of the two distractor-present conditions, $t(19) = 5.91$, $p < .001$, $d = 1.32$. The second comparison tested whether RTs were significantly faster if a distractor appeared in the frequent hemifield as compared to the rare hemifield, which was supported by the data, $t(19) = -2.10$, $p = .025$, $d = 0.47$. This means that even though distractor position repetitions were excluded by the design, Experiment 3 yielded comparable results to Experiment 1: Interference by a salient but irrelevant distractor was reduced if it appeared at a frequent, as compared to a rare, distractor location. This supports the conclusion that the probability cueing effect observed in Experiment 1 is not only owing to intertrial facilitation due to distractor position repetitions, but is also driven by statistical learning, which takes place even if there are no distractor position repetitions.

GENERAL DISCUSSION

Taken together, the present results clearly demonstrate that there is a probability cueing effect for distractor locations: observers can take advantage of uneven spatial distributions of distracting objects to minimize interference by distractors at probable locations, as compared to distractors at less probable locations. The main goal of the present study was to examine the causal mechanism of this probability cueing modulation for distractor locations: do observers minimize interference by distractors in probable distractor positions because a distractor appearing at a probable position is more likely to appear at the position of a distractor on the previous trial (thus benefitting from intertrial facilitation) or is there an additional benefit of statistical learning of the spatial distractor distribution? To answer this question, we investigated both intertrial facilitation by distractor position repetitions and statistical learning of uneven spatial distractor distributions, independently of each other. Experiments 2 and 3 demonstrate that both of these factors yield a reduction of distractor interference – even in the absence of the respective other influencing factor. Experiment 2 showed that distractor position repetitions can lead to reduced distractor interference (as compared to distractor position switches) – despite the absence of an uneven spatial distractor distribution, that is, without any particular incentive to shield a recently encountered distractor position. Experiment 3, on the other hand, showed that uneven distractor distributions lead to reduced interference from distractors in probable areas, as compared to distractors in less probable areas – despite the absence of distractor position repetitions, that is, when intertrial facilitation effects are effectively prevented.

The observed individual benefits of intertrial facilitation (Experiment 2) and statistical learning (Experiment 3) were both smaller (in RT magnitude and effect size) than the combined effect observed in Experiment 1. In Experiment 2, repeating the distractor position (as compared to switching the distractor position) led to an interference reduction of about 26 ms (d = 0.64). In Experiment 3, a distractor in a frequent area caused 26 ms less interference than a distractor in a rare area (d = 0.47). In Experiment 1, the uneven spatial distractor distribution was confounded with distractor position repetitions, that is, both factors could contribute to the benefit of probable versus less probable distractor regions. The observed benefit in this experiment was about 46 ms (d = 1.18), which corresponds roughly to the sum (52 ms) of the separate benefits caused by intertrial facilitation (Experiment 2) and statistical learning (Experiment 3) alone.

The finding that both intertrial facilitation and statistical learning contribute to the probability cueing effect for distractor positions is in line with various other studies that examined probability cueing effects for target positions. For instance, Geng and Behrmann (2005) reported greater intertrial facilitation effects in a highly probable, as compared to a less probable, target region and thus concluded that there is "facilitation for high probability location targets over and above that of spatial repetition priming alone" (p. 1257). Druker and Anderson (2010) used continuous spatial target distributions across the display, thus creating a design that led to only very few spatial target repetitions. Nevertheless, they observed probability cueing effects and accordingly concluded that intertrial facilitation alone cannot account for probability cueing of target locations. On the other hand, there are reports claiming that probability cueing (for target locations) depends solely on intertrial facilitation (Walthew & Gilchrist, 2006) or that intertrial facilitation is a prerequisite for (additional) statistical learning effects to occur (Kabata & Matsumoto, 2012). This is not in line with the present results for distractor position probability cueing: Statistical learning of distractor positions led to a probability cueing effect – even in the absence of distractor position repetitions (Experiment 3).[17]

The present finding of reduced distractor interference for distractors in frequent (i.e., likely), as compared to rare (i.e., unlikely), distractor locations is also in line with findings demonstrating that endogenous cueing of a likely distractor location can be used to actively inhibit that location, thereby reducing interference by a distractor appearing there (Munneke, Van der Stigchel, & Theeuwes, 2008; Van der Stigchel & Theeuwes, 2006). However, note that Jiang, Swallow, and Rosenbaum (2013) have recently compared the effects of endogenous cueing and statistical learning of target positions and concluded that the underlying attentional sources of those two effects are different. The present results demonstrate that not only endogenous cueing of likely distractor locations can be used to down-modulate interference by distractors appearing at these locations, but that probability cueing likewise has the potential to do so.

Investigating probability cueing of distractor locations (as opposed to probability cueing of target locations), and thus presenting singletons defined in two different feature dimensions, as in the present paradigm, may offer new insights into the potential mechanism underlying the probability cueing effect. On the one hand, probability cueing of locations

[17] Keep in mind that in Experiment 3, as in Experiment 2, target and distractor positions were restricted to six positions on the middle circle of the stimulus display. Consequently, distractors in trial n also never appeared on a position directly adjacent to the position of a distractor in trial n-1, most likely ruling out the possibility of spreading positional inhibition contributing to the observed probability cueing effect.

might be a purely spatial mechanism, involving (coarse-grained) spatial suppression or, respectively, enhancement of visual coding. On the other hand, probability cueing might also involve a feature- or dimension-based component, that is, selectively influencing the processing of certain features or feature dimensions (at certain locations). The latter is a central component of Guided-Search-type models of visual attention (e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989), which assume a processing architecture in which local feature contrast signals are first calculated in parallel (within separate dimensions). These signals can then be top-down modulated, or “weighted”, prior to their integration into a master salience map, which guides the deployment of attention. Hence, according to these models, the reduction of interference by salient, but irrelevant distractors might be owing to top-down up-weighting of the target-defining feature or feature dimension at the expense of the distractor-defining feature or feature dimension; or, likewise, to down-weighting (or “shielding”) of the distractor feature or dimension to the benefit of the target feature or dimension (e.g. Müller et al., 2009; Zehetleitner, Goschy, & Müller, 2012). To account for the present findings, such models would have to be extended by a spatial weighting component. For instance, it is conceivable that both feature-/dimension- and location-based weighing mechanisms may influence salience-based feature contrast signals prior to their integration into a master salience map (see Krummenacher, Müller, Zehetleitner, & Geyer, 2009, for a more detailed discussion of how these two mechanisms might interact).

CONCLUSION

The present study investigated probability cueing of distractor locations and its underlying mechanisms. We demonstrate that observers can take advantage of an uneven spatial distribution of distractor locations to reduce interference by distractors at probable locations as compared to distractors at less probable locations – that is, probability cueing of distractor locations can serve as an effective attentional cue guiding the shielding of likely distractor locations. We have identified both intertrial facilitation arising from repeating a distractor location and statistical learning independently of distractor position repetitions as (additively) contributing to the observed probability cueing modulation – in line with previous reports of probability cueing of target locations (e.g., Geng & Behrmann, 2005; Druker & Anderson, 2010).

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3 General Discussion

The present dissertation investigated several factors of influence on top-down shielding from distraction: prior experience with distractors, intra- vs. cross-dimensionality of distractors, time, and shielding incentive. In the following, the main results for each factor of influence will be summarized and discussed. Subsequently, an outlook on possible future directions will be given, which will be followed by a final conclusion.

3.1 Synopsis of results

The results of Study 1 have demonstrated an essential role of **prior experience** with distractors for effective top-down distractor shielding: Even when observers were induced to use a feature search mode, i.e. a goal-directed search strategy (e.g., Bacon & Egeth, 1994, Leber & Egeth, 2006b), distractor practice was essential for effectively avoiding distractor interference, and both for feature search mode observers and singleton detection mode observers distractor interference was reduced as a function of increasing distractor practice. On a general level, the presently observed essential role of prior experience with distractors is in line with previously discussed findings by Müller et al. (2009), who showed that distractor interference in subsequent blocks is reduced, if observers are first presented with a block containing 100% distractors relative to a block containing 0% distractors. The finding that even in feature search mode, distractor experience is necessary to prevent distractor interference is in line with recent results by Vatterott and Vecera (2012b): They presented their observers with five blocks of feature search mode trials (comparable to the feature search training phase trials of the present Study 1); the first block was a practice block and did not contain any distractors, in each of the subsequent blocks a different color distractor was presented on half of the trials. The results showed that there was significant interference during the respective first halves of the blocks, which was no longer present during the second halves of the blocks. Accordingly, distractor interference could only be effectively avoided after sufficient practice with a distractor feature. The finding that practice with one distractor color feature did not generalize to other distractor color features is in line with the results of the present Experiment 4 of Study 1, where practice with one distractor color feature during the feature search training phase was not sufficient to avoid distractor interference by another distractor color feature during the subsequent test phase.

Taken together, the results of the present dissertation also show that prior experience with distractors does not only contribute to top-down distractor shielding in terms of “distractor practice”: The results of Study 3 demonstrate that prior experience with spatially unevenly distributed distractors can initiate statistical learning, which leads to reduced interference by distractors in likely distractor regions as compared to distractors in unlikely distractor regions. The results of Study 3 also suggest an important contribution of prior experience with distractors on a more short-term time scale: Distractor interference was considerably reduced if a distractor reappeared at a recent distractor location compared to it changing its position. Similar short-term modulations have also been described by Müller et al. (2009; see also Geyer et al., 2008; Zehetleitner et al., 2009), who found distractor interference to be reduced following distractor-present trials compared to distractor-absent trials. Short-term modulations of this kind could be interpreted as observers carrying over a certain recently established shielding routine from one trial to the next.

The results of Study 1 are also informative regarding **intra- vs. cross-dimensionality** of distractors: Experiment 3 of Study 1 has shown that even observers, who were trained to use a feature search mode, were unable to effectively prevent distractor interference by intra-dimensional distractors, i.e. distractors defined in the same dimension as the target. This is in line with previous research (e.g., Kumada, 1999), which has shown that top-down distractor shielding is not as effective with intra- compared to cross-dimensional distractors. However, observers in the present experiment were trained to use a feature search mode, that is unlike for instance Kumada’s (1999) study, the present results are not vulnerable to the criticism that observers used a singleton detection mode and could not avoid interference by intra-dimensional distractors due to this. Accordingly, the fact that feature search mode observers were unable to effectively shield against intra-dimensional distractors argues against the notion of independent feature weighting as mechanism of the feature search mode: If this were the case, distractors not sharing the target defining feature should not cause any distractor interference in feature search mode, irrespective of whether they are defined in the same or a different dimension as the target.

One alternative mechanism to independent feature weighting is “hierarchical feature weighting” or “dimension weighting” as suggested by the *dimension-weighting account* (e.g., Found & Müller, 1996; Müller et al., 1995; Müller et al., 2003). According to this idea, the up- or down-weighting of one feature will always bring along an up- or down-weighting of all other features defined in the same dimension. Here, the present results are inconclusive: On the one hand the results of Experiment 5 of Study 1 demonstrate that observers can utilize distractor practice with one shape distractor to effectively shield against distractor interference by another shape distractor, which is in line with the hierarchical weighting idea. On the other hand, however, the same was not true for the color dimension: The results of Experiment 4 of Study 1 show that observers could not utilize distractor practice with one color distractor to effectively avoid distractor interference by another color distractor, which would have also been expected by the hierarchical weighting idea. This is in line with the aforementioned results of Vatterott and Vecera (2012b), who similarly found that in feature search mode, practice with one distractor color feature is not sufficient to avoid distractor interference by another distractor color feature. It is possible that the color dimension differs from other feature dimensions; Found and Müller (1996) for instance have suggested that one could "conceptualize the color dimension as further subdivided into subdimensions representing broad categories of color" (p. 100). Following this suggestion, one could hypothesize that practice only carries over from one color distractor to another color distractor, if both distractor color features belong to the same color subdimension.

Study 2 investigated **time** as factor of influence on top-down shielding from distraction in saccadic target selection. In line with previous results (e.g., van Zoest et al., 2004; van Zoest & Donk, 2008) it was found that top-down control over early saccadic target selection increased in magnitude with increasing saccadic latencies, i.e. over time: The longer the saccadic latencies, the more saccades observers could direct to the target item in comparison to the distractor item. However, the results of the present Study 2 also show that top-down control over early (short-latency) eye-movements is indeed possible and non-negligible in magnitude: When target and distractor were of comparable salience, the distractor was selected considerably less often than the target; there were even distractors slightly more salient than the target, which were selected considerably less often than the target. In addition, the presently used salience estimation procedure allowed quantitatively estimating the salience difference (between target and distractor), at which both would be selected with equal probability (by short-latency eye movements): A distractor would have to be detected 38 ms faster than the target during the salience estimation procedure to attract the same amount of short-latency eye movements, i.e. it would have to have a considerable bottom-up salience advantage. Estimating the salience difference point of equal selection probability can serve as a quantitative indicator of the top-down control applied (similar to the "difference scores" suggested by van Zoest & Donk, 2008). Establishing such a quantitative indicator of top-down control can provide useful in future research, since it allows comparing the top-down control applied under different conditions (e.g., early vs. late in time). Taken together, the results of Study 2 suggest that concerning the magnitude of top-down control, there is no categorical difference between early and later time windows, since already early in time (i.e., with short-latency eye movements), strong indications of top-down distractor shielding were observable. Instead, the results suggest a continuum model of distractor shielding, according to which the magnitude of top-down control increases gradually over time (see also van Zoest & Donk, 2008, for a similar suggestion).

The results of Study 3 have shown that observers' **shielding incentive** can be "fine-tuned" to specific distractor locations, which are likely to contain salient, but irrelevant distractors: Distractor interference by distractors in frequent distractor regions was reduced compared to distractor interference by distractors in rare distractor regions. This suggests that observers selectively shielded certain regions of the visual field, for which they had a high shielding incentive, since they were very likely to contain distractors. In addition, this shows that so-called "probability cueing" can not only selectively facilitate target detection for targets in frequent locations compared to targets in rare locations (e.g., Geng & Behrmann, 2002, 2005), but can also selectively facilitate distractor shielding against distractors in frequent distractor locations as compared to distractors in rare distractor locations (see also Reder et al., 2003). Finally, the results of Study 3 suggest that both intertrial facilitation, i.e. distractor position repetitions and statistical learning, irrespective of distractor position repetitions, contribute to probability cueing for distractor locations.

The finding that intertrial facilitation alone cannot account for probability cueing is in line with very recent results of Jiang, Swallow, Rosenbaum, and Herzig (2013, Experiment 1) concerning probability cueing of target locations: They had their observers search for a T among Ls. During a training phase, the target appeared with 50% probability in one of the four quadrants of the search display, i.e. it was three times more likely to appear there than in any of the other three quadrants. In the subsequent test phase, the target appeared equally likely in each of the four quadrants. In the training phase, response times were significantly faster, when the target appeared in the frequent quadrant as compared to the rare quadrants. Critically, probability cueing in the training phase (where target appearance was unevenly distributed across the quadrants) did not depend on intertrial facilitation, i.e. there was no significant interaction between target quadrant repetition and probability cueing. Most importantly, however, the probability cueing effect was maintained throughout the subsequent test phase (where target appearance was evenly distributed across the quadrants), i.e. response times continued to be significantly reduced for the previously frequent quadrant compared to the previously rare quadrants – despite the target now appearing equally likely in each quadrant. As the target in the test phase appeared equally likely in each quadrant, target quadrant repetitions were similarly equally likely for each quadrant. Taken together, those findings suggest that intertrial facilitation (i.e., target quadrant repetitions) cannot be the single mechanism underlying probability cueing. The finding that in Jiang et al.'s (2013) study a once-established spatial attentional bias was carried over to a subsequent test phase, where it no longer was beneficial, also has other important potential implications, which will be followed-up upon in the subsequent section.

3.2 Future directions

In the following, possible future directions building on the presently reported results will be discussed. Concerning prior experience with distractors, one salient starting point for future research is the transferability or generalization of distractor practice effects: For instance, the present results have shown that (even in feature search mode) distractor practice with one distractor color feature is not sufficient to effectively avoid distractor interference by another distractor color feature (see also Vatterott & Vecera, 2012b). However, recent evidence (Vatterott & Vecera, 2012a) suggests that when observers are presented with diverse distractor color features during training blocks (i.e., randomly with one of three different color features), they are able to utilize this practice to effectively avoid distractor interference by a novel fourth distractor color feature in a subsequent test block. This is in line with results by Kelley and Yantis (2009): They found that when observers practiced with distractors, which were rather consistent in appearance, this practice effect did not transfer to novel distractors. By contrast, when observers practiced with more diverse distractors, there was evidence for generalization of this practice effect. However, the latter generalization effect was operationalized as transfer from old distractor locations to new distractor locations (as opposed to old and new distractor features); it is therefore unclear what this reveals about transfer from one distractor feature (or dimension) to another distractor feature (or dimension). Nevertheless, carry-over of distractor practice seems to be possible under certain conditions and future research should continue to investigate the prerequisites and boundary conditions of distractor practice generalization.

The question, under which conditions distractor practice with one distractor feature transfers to other distractor features, is also related to the presently investigated hierarchical feature weighting or dimension weighting idea (e.g., Found & Müller, 1996; Müller et al., 1995): As has been previously discussed, the present results suggest that top-down distractor shielding is hierarchically organized, that is, acquiring a shielding routine with one distractor feature can facilitate shielding against another distractor feature of the same dimension. However, this was observed only for the shape dimension (Study 1, Experiment 5), but not for the color dimension (Study 1, Experiment 4). Future research could focus on investigating the reasons for this: For instance, it is possible that the color dimension differs from other feature dimensions and consists of several subdimensions, each representing broad categories of color and behaving like single feature dimensions (Found & Müller, 1996). Accordingly, prior experience, with one color feature should not necessarily facilitate distractor shielding against another distractor feature. In line with this, Meeter and Olivers (2006, Experiment 3) reported feature-specific short-term prior experience effects: In their experiment, observers had to search for a red or green target, while a blue or yellow distractor was present in half of the trials: In the distractor-present condition, response times were significantly faster if the distractor color repeated rather than changed. Feature-specific short-term prior experience effects of this kind argue against a dimension-based shielding mechanism for the color dimension. However, it is unclear, whether this finding is stable: For instance, Theeuwes et al. (2000, Experiment 3) had their observers search for a shape-defined target item. A color-defined distractor, which was either red or green, did not produced any feature-specific short-term prior experience effects; that is, unlike in Meeter and Oliver's (2006, Experiment 3) study, response times were not significantly faster when the distractor color repeated rather than changed. Null-findings of this kind would be consistent with a dimension-based shielding mechanism for the color dimension. Further, as outlined above, Vatterott and Vecera (2012b) reported that (in feature search mode) distractor practice with one distractor color feature does not carry-over to another distractor color feature; which would argue against a dimension-based shielding mechanism for the color dimension. However, Vatterott and Vecera (2012a) also showed that when (feature search mode) observers practiced with *diverse* distractor color features, this distractor practice carried over to a novel distractor color feature; which would be in line with a dimension-based shielding mechanism for the color dimension. Accordingly, top-down shielding against color distractors appears to be feature-based under certain circumstances and dimension-based under other circumstances; future research should try to specify, which circumstances induce which kind of top-down shielding against color distractors.

In the present Study 2, a quantitative indicator of top-down shielding from distraction was introduced: the estimated salience difference point of equal selection probability between a target and a cross-dimensional distractor. Having established such an indicator, it can be used to compare the magnitude of top-down modulations under different conditions. For instance, one could systematically investigate differences in top-down shielding magnitude for intra- and cross-dimensional distractors to further investigate the hierarchical feature weighting idea (e.g., Found & Müller, 1996; Müller et al., 1995): If the weighting of one feature would automatically imply an increased weighting for all other features of the same dimension, then the salience difference point of equal selection probability for intra-dimensional distractors should be considerably smaller than the salience difference point of equal selection probability for cross-dimensional distractors – or even close to zero.[18] However, again, there may be differences between the color dimension and other feature dimensions. If indeed, as previously discussed, the color dimension exists of multiple subdimensions (Found & Müller, 1996), the point of equal selection probability for intra-dimensional color distractors should be larger than for other intra-dimensional distractors.

Concerning distractor shielding induced by probability cueing, future research should focus on the underlying mechanism of this effect: Is it purely spatial in nature, i.e. a location-based down-weighting mechanism for frequent distractor locations; or does it involve a feature- or dimension-based mechanism, which allows selectively modulating the weights of certain features or dimensions at certain locations? Investigating this question is potentially relevant for Guided-Search-type models of visual attention (e.g., Wolfe, 1994; Found & Müller, 1996), since location probability cueing effects suggest that those models would have to be extended by a location-based weighting mechanism (see also Krummenacher, Müller, Zehetleitner, & Geyer, 2009). Further, future research on distractor shielding induced by probability cueing should focus on the persistence of this effect: As previously discussed, Jiang et al. (2013) have shown that a once-established spatial attentional bias for target items (induced by probability cueing), continues to persist over several hundred trials after the target is no longer unevenly distributed, i.e. after such a spatial attentional bias is no longer beneficial. This was true even when there was a one week delay between the training phase with unevenly distributed target items and the test phase with evenly distributed target

[18] In the present context, a “smaller” point of equal selection probability refers to the distractor having a smaller salience advantage over the target; a point of equal selection probability close to zero implies that target and distractor are similar in salience.

items. Accordingly, Jiang et al. (2013) concluded that the “stubborn persistence of this learned attentional bias, even in situations where they could impair performance, differentiates experience-driven attention from goal-driven attention” (p. 95). In the present dissertation, selective distractor shielding induced by probability cueing has mostly been discussed in terms of top-down control. This interpretation loosely follows Müller et al. (2009), who observed reduced distractor interference with overall high distractor prevalence compared to overall low distractor prevalence and discussed this in terms of observers having a higher incentive for distractor shielding with frequent distractors compared to rare distractors. Future research should investigate whether the presently observed distractor interference modulation induced by probability cueing is indeed a top-down effect (due to an increased shielding incentive for frequent compared to rare distractor position) or rather attributable to “experience-driven attention” as discussed by Jiang et al. (2013) for target-related probability cueing effects.

Finally, and most importantly, future research should focus on relationships and possible interaction effects between the presently discussed factors of influence on top-down shielding from distraction: For instance, the present dissertation has shown that prior experience with distractors decreases the magnitude of distractor interference effects and that early top-down control (in saccadic target selection) can be strong enough to overcome the bottom-up advantage of salient, but irrelevant distractors – but, can prior experience with distractors further increase the magnitude of early top-down control? In addition, results from the present dissertation suggest that distractor interference from intra-dimensional distractors cannot be as effectively down-regulated as distractor interference from cross-dimensional distractors – does this mean that top-down distractor shielding against intra-dimensional distractors can not at all benefit from prior experience with distractors or an increased shielding incentive? Or is distractor shielding against intra-dimensional distractors simply limited in magnitude, but also possible to a certain degree (given certain circumstances; e.g., prior distractor experience)? Investigating connections of this kind could be an important source of knowledge about the underlying mechanisms of visual attention.

3.3 Conclusions

Taken together, the present results have demonstrated that top-down shielding from distraction is influenced by various factors of influence, i.e. whether or not observers are able to avoid distraction by salient, but irrelevant stimuli is dependent on various circumstances: Top-down shielding from distraction seems to be more effective with prior distractor practice than without such practice, with cross-dimensional compared to intra-dimensional distractors, later than earlier time, and finally, for distractors appearing in frequent distractor locations compared to rare distractor locations.

Modulations of this kind are difficult to reconcile with the initial strong version of the *automatic-attentional-capture account* (Theeuwes, 1992), which states that preattentive parallel search cannot be subject to top-down control, and thus, distractor interference by distractors more salient than the target should not be modifiable. Accordingly, distractor interference should not be modulated dependent on prior experience with a distractor or on the distractor appearing in a frequent compared to a rare distractor position – since there was no change in physical salience of the distractor. The current version of the automatic-attentional-capture account (Theeuwes, 2010) could account for these findings by assuming that while there is initial attentional capture by salient distractors (which is not under top-down control), the magnitude of distractor interference is ultimately determined by the speed of attentional disengagement from the distractor location (which is under top-down control); thus initial attentional capture might happen for both distractors in frequent and rare distractor areas, but top-down attentional disengagement could be more efficient for distractors in frequent compared to rare distractor areas; similarly while initial attentional capture might happen with and without prior distractor practice, top-down attentional disengagement could become more efficient with increasing distractor practice.

Several of the present findings are also difficult to reconcile with the idea of two distinct search strategies, a goal-directed feature search mode and a stimulus-driven singleton detection mode, as suggested by the *search-mode account* (Bacon & Egeth, 1994): For instance, without prior distractor practice, observers induced to use a feature search mode were as unable as observers induced to use a singleton detection mode to prevent distractor interference (Study 1). In addition, the ability for top-down distractor shielding in saccadic target selection increased rather gradually with increasing saccadic latency (Study 2), which cannot be accounted for by two distinct search strategies (see van Zoest et al., 2004, for a more detailed discussion of this). Even if one would assume that observers initially (early in time) operate a singleton detection mode and then (later in time) switch to a feature search mode (as for instance discussed by van Zoest et al., 2004), this would be difficult to reconcile with the present findings, since already short-latency (early) saccades were influenced by top-down control, which according to the search-mode account (Bacon & Egeth, 1994) should not be possible in singleton detection mode. Finally, reduced distractor interference for distractors in frequent distractor positions compared to distractors in rare distractor positions (Study 3), could only be accounted for, if one assumes that observers rapidly switch between search modes and use a feature search mode for frequent distractor positions and a singleton detection mode for rare distractor positions.

The present findings can probably best be accounted for by Guided-Search-type models of visual attention (e.g., Wolfe, 1994; Found & Müller, 1996), which assume that the experienced distractor interference is determined by the relative strengths of the bottom-up activation of the irrelevant distractor and the top-down attentional weight setting for the target-defining feature or dimension. Concerning those models, the present dissertation makes several suggestions or refinements: (i) the efficiency of top-down attentional weight settings improves with prior distractor practice (see also Müller et al., 2009); (ii) top-down attentional weight settings seem to be hierarchically organized – at least for the shape dimension, but not necessarily for the color dimension; (iii) the influence of top-down attentional weight settings on the overall master salience map apparently increases over time (see also van Zoest et al., 2004) – nevertheless, a non-negligible influence of top-down attentional weight settings is already observable early in time; (iv) top-down attentional weight settings can be induced by spatial probability cueing.

On a more general level, when searching for an object, which is not the physically most salient one in the environment, whether or not the goals and intentions of an observer can be strong enough to ignore the conspicuity of irrelevant objects is (among others) dependent on several factors: The search will be less impaired by irrelevant objects (i) if the observer has already had (recent) experience with ignoring similar irrelevant distractors; (ii) if the object the observer is looking for is defined by different dimensional attributes than the distractors; for instance, when searching for a circular object, pink distractors should be easier to ignore than oval distractors; (iii) if the search is rather slow compared to fast; (iv) if the distracting objects appear in locations where distractors are expected to appear compared to surprising or rare distractor locations.

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Curriculum Vitae

Harriet Goschy

Born on 25.02.1986 in Hatzfeld, Romania.

Education

2010 – 2014	Ph.D. in Systemic Neurosciences, Graduate School of Systemic Neurosciences, Ludwig-Maximilians-Universität München
2005 – 2010	Diploma in Psychology, Ludwig-Maximilians-Universität München
1996 – 2005	Abitur, Holbein-Gymnasium Augsburg

Research Experience

2010 – 2013	Research Assistant Chair of General and Experimental Psychology Ludwig-Maximilians-Universität München

List of Publications

Journal Articles

Goschy, H., Koch, A. I., Müller, H. J., & Zehetleitner, M. (2014). Early top-down control over saccadic target selection: Evidence from a systematic salience difference manipulation. *Attention, Perception, & Psychophysics, 76(2)*, 367-382.

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* Both authors contributed equally to the study.

Conference Articles

Groten, R., Feth, D., **Goschy, H.**, Peer, A., Kenny, D. A., & Buss, M. (2009). Experimental analysis of dominance in haptic collaboration. *18th IEEE International Symposium on Robot and Human Interactive Communication*. Toyama, Japan.

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Goschy, H., Müller, H. J., & Zehetleitner, M. (2010). Dimensions- oder merkmalsbasierte Gewichtung: Wie spezifisch ist der Feature-Search-Modus? In C. Frings, A. Mecklinger, D. Wentura, & H. Zimmer (Eds.), *Beiträge zur 52. Tagung experimentell arbeitender Psychologen* (p. 244). Lengerich: Pabst Science Publishers.

Affidavit / Eidesstattliche Versicherung

I hereby confirm that the dissertation “**Top-down shielding from distraction in visual attention: Factors of influence**” is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation “**Top-down shielding from distraction in visual attention: Factors of influence**” selbstständig angefertigt habe, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

Munich, 20th of February 2014

München, 20. Februar 2014

Harriet-Rosita Goschy

Author Contributions

Study 1: Zehetleitner, M.*, **Goschy, H.***, & Müller, H. J. (2012). Top-down control of attention: It's gradual, practice-dependent, and hierarchically organized. *Journal of Experimental Psychology: Human Perception and Performance, 38(4),* 941-957.

* Shared first authorship: Both authors contributed equally to the study.

HG and MZ share first authorship. Parts of the experimental work for this study were done in the context of the diploma thesis project of **HG**, which was supervised by MZ. **HG** and MZ conceived and designed the experiments. **HG** collected and analyzed the data. **HG** discussed the results with MZ and HJM. **HG**, MZ, and HJM wrote the paper.

Study 2: **Goschy, H.**, Koch, A. I., Müller, H. J., & Zehetleitner, M. (2014). Early top-down control over saccadic target selection: Evidence from a systematic salience difference manipulation. *Attention, Perception, & Psychophysics, 76(2)*, 367-382.

HG, AIK, and MZ conceived the research. **HG** and MZ designed the experiments. **HG** collected and analyzed the data. **HG** discussed the results with MZ and HJM. **HG** wrote the paper. MZ and HJM commented on and revised the paper.

Study 3: **Goschy, H.**, Bakos, S., Müller, H. J., & Zehetleitner, M. (submitted). Probability cueing of distractor locations: Both intertrial facilitation and statistical learning mediate interference reduction.

Experiment 1 was carried out in the context of an undergraduate practical course on empirical psychology, which was taught by **HG**: **HG** conceived and designed Experiment 1; the between-subjects factor distractor frequency distribution (left/right vs. top/bottom) was incorporated following student suggestions. Data for Experiment 1 was collected by students of the aforementioned course. **HG** analyzed the data for Experiment 1 and discussed the results with the students. Parts of the experimental work for this study were done in the context of the bachelor thesis project of SB, which was supervised by **HG**. **HG** and SB conceived and designed Experiments 2 and 3. SB collected data for Experiment 2; SB and **HG** collected data for Experiment 3. **HG** and SB analyzed the data for Experiments 2 and 3, and discussed the results. **HG** discussed the results with MZ and HJM. **HG** wrote the paper. MZ and HJM commented on and revised the paper.

Munich,

Harriet-Rosita Goschy   Michael Zehetleitner   Hermann J. Müller