Attention, Perception, & Psychophysics
2009, 71 (8), 1760-1770
doi:10.3758/APP.71.8.1760

Additional-singleton interference in efficient visual search: A common salience route for detection and compound tasks

Michael Zehetleitner
Ludwig Maximilian University, Munich, Germany

Michael J. Proulx
Queen Mary, University of London, London, England

and

Hermann J. Müller
Ludwig Maximilian University, Munich, Germany

In efficient search for feature singleton targets, additional singletons (ASs) defined in a nontarget dimension are frequently found to interfere with performance. All search tasks that are processed via a spatial saliency map of the display would be predicted to be subject to such AS interference. In contrast, dual-route models, such as feature integration theory, assume that singletons are detected not via a saliency map, but via a nonspatial route that is immune to interference from cross-dimensional ASs. Consistent with this, a number of studies have reported absent interference effects in detection tasks. However, recent work suggests that the failure to find such effects may be due to the particular frequencies at which ASs were presented, as well as to their relative saliency. These two factors were examined in the present study. In contrast to previous reports, cross-dimensional ASs were found to slow detection (target-present and target-absent) responses, modulated by both their frequency of occurrence and saliency (relative to the target). These findings challenge dual-route models and support single-route models, such as dimension weighting and guided search.

Detection and attentional selection of a unique item in the visual scene are frequent requirements for observers in both natural and laboratory environments. In detection tasks, one decides whether a unique item (target) is present in or absent from a set of other items (nontargets, or distractors). By contrast, in compound tasks (Bravo & Nakayama, 1992; Duncan, 1985), one must attentionally select and further analyze the unique item in order to permit the reporting of some response-critical attribute. There is general agreement that the uniqueness of an item in the visual scene can be represented topographically in a saliency map (Itti & Koch, 2000; Koch & Ullman, 1985; Wolfe, 1994), but there is a debate about how this map is involved in detection and attentional selection.

Although some authors have assumed that both detection tasks and tasks involving attentional selection are processed via a saliency map—see, for instance, Found and Müller's (1996) dimension-weighting account (DWA), Wolfe's (1994) Guided Search 2.0 (GS), and Müller, Heller, and Ziegler (1995)—others have proposed a dual-route hypothesis. For example, feature integration theory (FIT; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Sato, 1990) assumes that only tasks involving attentional selection are processed via a master (saliency) map. In contrast, according to FIT, detection tasks are processed via so-called *dimensional modules*, which signal that a unique item is present within a particular dimension, but in a nonspatial manner; in other words, they signal the presence of, but not the location of, a unique item. Thus, if the target dimension is known in advance (within-dimension search), detection decisions can be based on monitoring the output of a single, prespecified module: "The 'odd one out' pops out *within* a single, prespecified dimensional module" (Treisman, 1988, p. 207). In contrast, when the singleton-defining dimension varies randomly across trials (cross-dimension search), "each different module may need to be separately checked to determine which of them contains the [odd-one-out item]" (Treisman, 1988, p. 207). This notion of dimensional modules was introduced to explain two findings—namely, singleton detection's being (1) faster in within-dimensional than in cross-dimensional search (see also Müller et al., 1995) and (2) faster when there is distractor heterogeneity in non-target-defining dimensions, rather than in the target-defining dimension.

The notion of dimensional modules has recently been revived by Chan and Hayward (2009) and Kumada (1999)

M. Zehetleitner, mzehetleitner@psy.lmu.de

on the basis of a comparison of detection tasks (for which spatial information is not strictly necessary) with compound and localization tasks, which require spatial information. Chan and Hayward found differences between nonspatial (i.e., detection) and spatial (i.e., compound and localization) search tasks in several respects—most important, in the present context, in terms of interference from additional, task-irrelevant singletons (Kumada, 1999; Theeuwes, 1992).

Additional-Singleton (AS) Paradigm

In the AS paradigm, the target may not be the only singleton item in the search display; rather, a task-irrelevant singleton item can be present as well. The basic finding in this paradigm is that reaction times (RTs) are slower when there is an AS in the display than when there is none (Theeuwes, 1992). Although this AS interference effect has been extensively investigated (e.g., Bacon & Egeth, 1994; Becker, 2007; Fecteau, 2007; Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Lamy, Tsal, & Egeth, 2003; Theeuwes, 1991, 1992; Yantis & Hillstrom, 1994), the paradigm used in these studies was typically a compound-search task. More relevant to the question at issue are studies of AS interference in detection tasks (Chan & Hayward, 2009; Kumada, 1999; Proulx & Egeth, 2006, 2008; van Zoest & Donk, 2004).

Kumada (1999) and van Zoest and Donk (2004) found ASs defined in the same dimension as the target (e.g., orientation), but by a different feature (e.g., ASs that were tilted 90º, as compared with targets that were tilted 45º, with respect to the vertical distractors), to disrupt processing in detection tasks. By contrast, whereas ASs defined in a dimension other than the target (e.g., color) caused interference in a compound task (the latter being basically a replication of Theeuwes, 1992), such singletons did not interfere with detection performance (Chan & Hayward, 2009; Kumada, 1999).

However, seemingly at variance with Chan and Hayward (2009) and Kumada (1999), Proulx and Egeth (2006, 2008) did report distraction effects from cross-dimensional ASs in detection tasks. Note, however, that search was inefficient in Proulx and Egeth's studies (i.e., the functions relating detection RT to the number of items in the display were not flat), so their findings may not generalize to efficient search, which is the focus of the present study.

Dual-Route Accounts

In summary, both Chan and Hayward (2009) and Kumada (1999) found interference from cross-dimensional ASs in compound and localization tasks, but not in detection tasks. From this dissociation (especially the null finding in detection tasks), they inferred that processing differs qualitatively between detection and compound/localization tasks. That is, the processing pathways mediating detection and compound/localization tasks separate early in processing, with the saliency map playing a role only in spatial tasks. In detection tasks with a fixed (or known) target dimension, dual-route accounts assume detection decisions to be based solely on the corresponding dimensional module (Figure 1). Since the accumulation of evidence in this module would not be influenced by feature contrast signals in a different dimensional module, there would be no interference from cross-dimensional ASs in detection tasks.

Kumada (1999) proposed an alternative dual-route model. He assumed two routes along the lines of Ungerleider and Mishkin's (1982) notion of functionally separate *where* and *what* pathways. Compound tasks are processed via the *where* pathway, which is vulnerable to cross-dimensional AS interference and unaffected by dimensional weighting; dimensional weighting, in contrast, affects the accumulation of evidence in the *what* pathway, which is unaffected by cross-dimensional AS interference.

In summary, regardless of the precise implementation of the dual routes, the second, nonspatial route has three key features: (1) Detection tasks are solved via this second route, rather than via the salience map; (2) the detection route is spatially nonspecific; and (3) the detection route is dimensionally segregated, so that the accumulation of evidence in the channel for one dimension is unaffected by evidence accumulated in other dimensional channels.

Purpose of the Present Study

Since the evidence for the dual-route models of Chan and Hayward (2009) and Kumada (1999) is essentially based on a null finding—namely, the absence of (significant) interference from cross-dimensional ASs in detection tasks—these models would be seriously challenged by any positive finding of interference in such tasks. Given this, the present study investigated two situations known to increase the strength of interference in compound tasks: the frequency with which ASs occur (Müller, Geyer, Zehetleitner, & Krummenacher, 2009) and their saliency relative to that of the target (e.g., Theeuwes, 1992). The dual-route hypothesis would be strengthened by the finding that cross-dimensional ASs do not interfere with detection, even in situations known to produce greater interference in compound tasks. However, if interference is positively established under these conditions, the core assumption of dual-route models—namely, that the detection route is free from cross-dimensional interference as a matter of architectural principle—becomes untenable. Furthermore, if interference is mediated by the same mechanisms in detection and compound tasks, manipulations that are known to modulate the size of interference in compound tasks, such as the relative salience and spatial distance between the target and the AS, would be expected to do so also in detection tasks. This was investigated in the present study by examining the effects of these two variables in a detection task.

Why would a manipulation of AS frequency increase the interference effect in detection tasks? In a compound task, Müller et al. (2009) demonstrated that the strength of interference from ASs (which are of a constant higher saliency than the target singletons are) critically depends on how frequently they are presented in a given block of trials: The larger the proportion of trials with an AS, the smaller the interference. For example, in Müller et al.'s (2009) Experiment 2, the interference dropped from 70 msec for an experimental group with 20% AS to 20 msec for a group with 80% AS. That is, the distracting effect of physically identical ASs was modulated by the

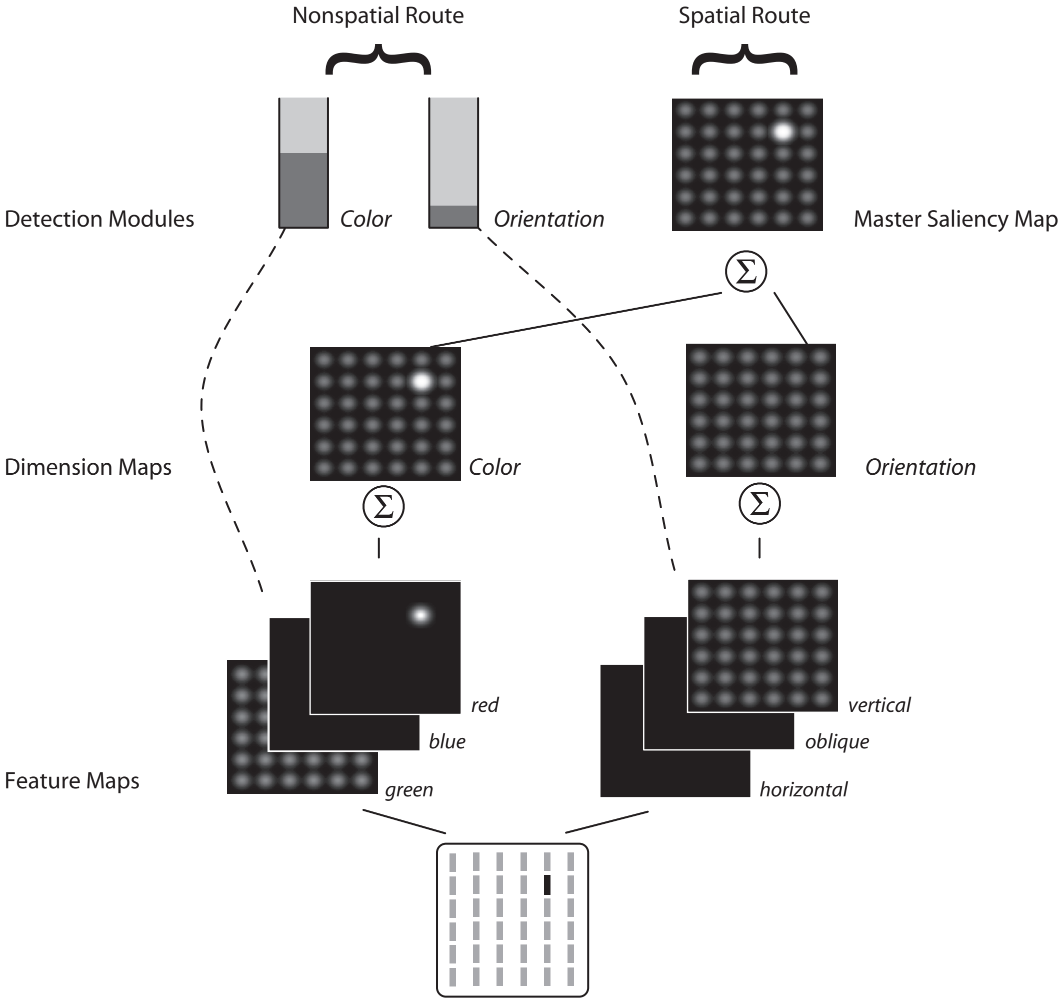

Figure 1. Dual- and single-route models agree in the assumption that the visual field is analyzed topographically in terms of feature-contrast, dimension-specific salience maps that are pooled into a master salience map in a spatial route. In addition to single-route models, which assume detection, localization, and compound tasks to be processed via the salience map, dual-route models assume an additional nonspatial route for singleton detection only. In the search displays, light gray stands for green bars and black stands for a red bar.

frequency of their occurrence. To explain this effect, Müller et al. (2009) proposed that observers can (top-down) suppress the AS-defining dimension and that they can use such a suppression strategy more consistently the more frequently ASs occur.

With regard to the present issue of single- versus dual-route models, it is important to note that both Chan and Hayward (2009) and Kumada (1999) presented ASs in 100% of their trials and compared performance to that in blocks in which no ASs could occur, where a 100% frequency of ASs was the very condition in which, according to Müller et al. (2009), the interference effect should be minimal (i.e., smaller than with, say, 50% AS). Given this, the present Experiment 1 varied the frequency of cross-dimensional ASs in a detection task with either 100% AS (basically a replication of Chan & Hayward, 2009, and Kumada, 1999) or 50% AS. The predictions of dual-route models are clear: Because the detection route is, by its very architecture, free from cross-dimensional interference, the frequency manipulation in Experiment 1 should have no effect; that is, there should be no interference under any condition (50%, 100%). By contrast, one-route models predict that interference from cross-dimensional ASs is greater in the 50%-AS than in the 100%-AS condition, because detection tasks are processed via the same pathway (up to the stage of the salience map) as compound tasks, for which Müller et al. (2009) had demonstrated a frequency effect.

Why would the salience of the AS, relative to that of the target, affect the interference effect in detection tasks? Theeuwes (1992), also in a compound task, compared the size of interference between conditions in which the AS was more and, respectively, less salient than the target, finding interference only in the former case. Generalizing from this, one might say that the more salient an AS is relative to the target, the larger the interference effect should be. This is because the target and the AS compete for focal-attentional selection in a race to be the first item to generate an above-threshold signal on the saliency map.

The competition is biased by the relative saliencies of the two singletons: The more salient the AS is, relative to the target, the more likely it is to win the race, thereby increasing the interference effect. Again, as with the manipulation of AS frequency (Experiment 1), the rationale of the present study (Experiment 2) was to manipulate the relative saliency of ASs and test the prediction of dual-route models that the detection route is, by principle, interference free. If it is, then even stronger (more salient) ASs would not lead to the manifestation of any interference effect.

Finally, the nonspatiality of the detection route—one of the core tenets of dual-route models—is examined in Experiment 3. If detection is processed via the salience map (as assumed by single-route models), there might be spatial modulations of the interference effect, depending on the distance between target and AS, as has recently been demonstrated for compound tasks: Theeuwes and Hickey (2008) found larger interference in a compound task the closer the AS was located to the target. Additionally, for the same separation of the AS from the target, the interference was larger if both singletons were positioned in the same hemifield. Dual-route models, by contrast, predict no spatial (distance- or hemifield-specific) modulation.

EXPERIMENT 1

In Experiment 1, we replicated the standard cross-dimensional AS paradigm with blocked presentation of the AS (100% vs. 0%). Additionally, a separate group of observers was presented with an AS randomly in only 50% of the trials. The dual-route hypothesis predicts no interference in either condition, because the task required simple detection. Since cross-dimensional ASs cannot interfere in the detection route, performance should not be influenced by how frequently an AS occurs in a trial block. In contrast, one-route accounts (such as the DWA) predict that interference effects would be larger in the randomized (50%) than in the blocked (100% vs. 0%) AS condition, analogous to the pattern observed in compound tasks.

Method

Participants. Twenty observers (13 female, 2 left-handed) with a median age of 23 years participated in Experiment 1.

Apparatus and Stimuli. Stimuli were presented on a 17-in. Sony Multiscan E250 monitor driven by a personal computer (PC) running under the Windows XP operating system. The experimental software was purpose-written in C++. The PC was placed in a sound-isolated chamber with a black interior. There was a dim background light to prevent reflections on the monitor. Viewing distance was about 60 cm, maintained by using a chinrest. The screen refresh rate was 85 Hz, and the screen resolution was 1,024 × 768 pixels. Participants reported target presence/absence by pressing the right or left button of a mouse using the index finger of their right and left hand, respectively. Response times and accuracy were recorded online by the computer.

The display consisted of 117 bars arranged in 13 rows of nine items. The dimensions of the bars in degrees of visual angle were 0.21º wide and 1.16º tall. Center-to-center distance between adjacent bars was 1.6º horizontally and 2.7º vertically, with a uniformly distributed spatial jitter of 0.2º. Targets differed from distractors in terms of orientation (randomly tilted 30º from the vertical to either the left or the right), both being green (26 cd/m^2, $x = 0.290$ and $y = 0.593$ CIE 1931 coordinates). ASs differed from distractors in color: They were of an equiluminant red (26 cd/m^2, $x = 0.620$ and $y = 0.496$ CIE 1931 coordinates).

Design. The main factor manipulated (between subjects) in Experiment 1 was the frequency of AS (see Table 1). There were two separate groups of participants who were presented with either 100% or 50% AS (interference condition). Additionally, both groups performed a condition with 0% AS (control condition).

For the 100%-frequency group, AS interference was calculated by subtracting the control (0%-frequency) condition RTs from the interference (100%-frequency) condition RTs. Analogously, for the 50%-frequency group, the interference effect was calculated as the difference between the interference (50%-frequency) and control (0%-frequency) condition RTs. For the 50%-frequency group, AS interference could be calculated in an additional way, on the basis of the trials from the interference (50%-frequency) condition only—that is, by comparing RTs between trials with and without an AS (both types of trials from the same interference condition).

To both groups, the interference (with AS) and the control condition (without AS) were presented in blocked fashion, with the order of conditions counterbalanced across participants. Both conditions consisted of 10 blocks of 60 trials each, totaling 1,200 trials per participant. Note that this manipulation of AS frequency is analogous to that used by Müller et al. (2009). In the control condition (which was the same in both frequency groups), an AS was never present. In the interference condition, an AS was present on each trial in the 100%-frequency group and on half of the trials (i.e., 30 trials per block) in the 50%-frequency group. The main factor of the detection task was target presence (50%-present and 50%-absent trials).

In summary, the experimental design comprised the between-subjects factor of frequency of ASs (100% vs. 50%) and the within-subjects factors of presence of AS (present vs. absent) and presence of target (present vs. absent). An additional between-subjects factor was the order of the interference and control conditions (interference condition in the first vs. the second half of the experiment).

Procedure. Each trial started with the presentation of a white fixation dot (radius = 0.2º) for a random duration ranging from 800 to 1,200 msec, with a mean duration of 1,000 msec. All stimuli appeared simultaneously and stayed on-screen until the participant responded. A response error was followed by an additional blank screen presented for 2 sec as a visual feedback signal. After each block of 60 trials, participants were shown their mean RTs and error rates for that block.

Results

RTs below 200 msec and above 1,200 msec were excluded from the analysis (<1% of all trials), as were response error trials (3.5% overall). See Figure 2 for the (correct) RTs in the experimental conditions of Experiment 1.

Analysis of both frequency groups. The (correct) RT data were examined by an ANOVA with the between-subjects factors order (control condition first vs. second) and frequency of AS occurrence (50% vs. 100%) and the within-subjects factors target presence (present vs. absent) and AS (present vs. absent). Note that, in this ANOVA, AS-present RTs were taken from the interference condition, and AS-absent RTs were taken exclusively from the

Table 1
Frequency of Additional Singleton Occurrence for the Different Experimental Groups and the Different, Blocked Experimental Conditions of Experiment 1

	Condition	
Frequency of Occurrence	Control	Interference
100%	0%	100%
50%	0%	50%

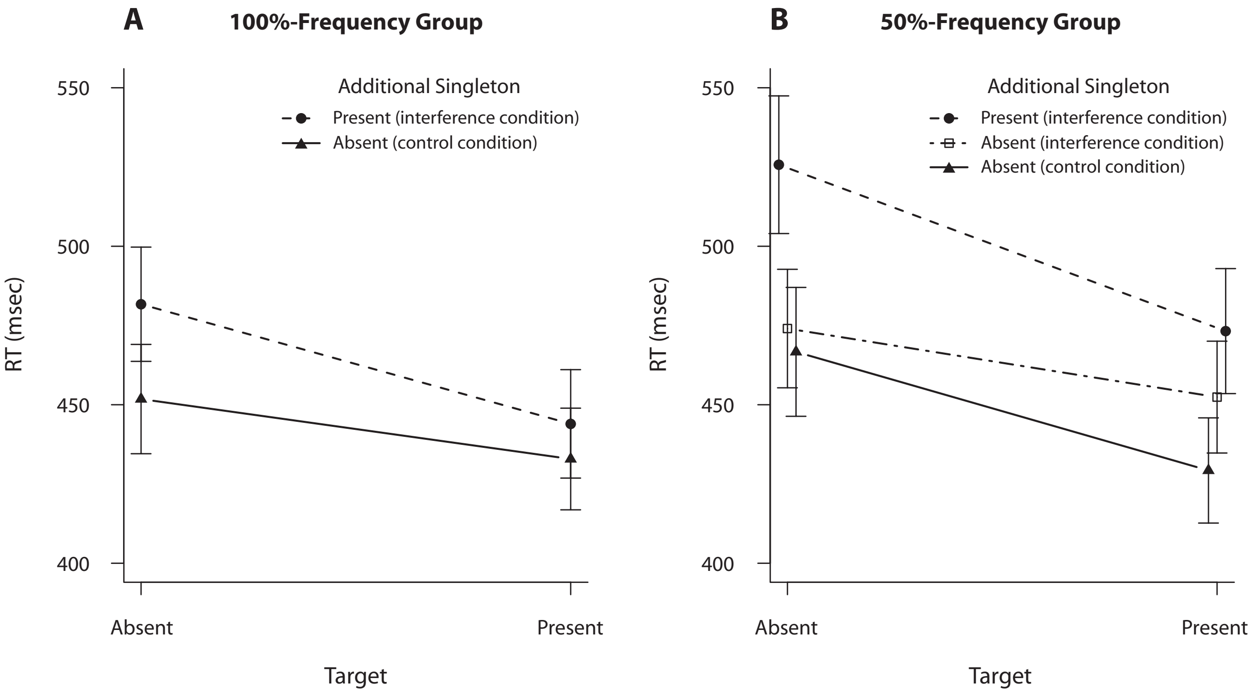

Figure 2. Mean reaction times (RTs, in milliseconds), as a function of target presence and AS presence in Experiment 1, separately for the 100%-AS (panel A) and 50%-AS (panel B) frequency groups. Bars represent standard errors of the means.

control condition. That is, AS-absent RTs from the interference condition of the 50%-frequency group were omitted in this analysis and analyzed separately (see below).

The ANOVA revealed significant main effects of target presence [$F(1,16) = 30.2$, $p < .001$] and AS presence [$F(1,16) = 44.3$, $p < .001$]. Target-present RTs were faster than target-absent RTs (445 vs. 482 msec), and the presence of an AS slowed search (present vs. absent: 482 vs. 445 msec). The main effects of order and of frequency of occurrence were nonsignificant (both Fs < 0.5). The interaction between target presence and AS presence was significant [$F(1,16) = 9.5$, $p < .006$], with the distracting effect of ASs being larger overall for target-absent than for target-present trials (45 vs. 28 msec). It is important that the interaction between presence of AS and frequency of occurrence was significant [$F(1,16) = 14.4$, $p < .001$], with ASs having an overall larger distracting effect in the 50%-frequency condition (52 msec) than in the 100%-frequency condition (20 msec). An analogous ANOVA of error rates revealed only one significant main effect: Error rates were higher when an AS was present (3.8%) rather than when it was absent (2.9%) [$F(1,16) = 5.2$, $p < .036$], indicating that the RT results were not contaminated by a speed–accuracy trade-off.

In a further analysis, the magnitudes of AS interference for the 100%-frequency and 50%-frequency groups were calculated separately for the target-present and target-absent conditions and compared against 0 (t tests, with Bonferroni-corrected p values). For the 100%-frequency group, the AS interference effect was 11 msec ($p > .17$, n.s.) and 30 msec ($p < .002$) for target-present and target-absent trials, respectively. For the 50%-frequency group, the corresponding effect sizes were 44 msec ($p < .001$) and 59 msec ($p < .001$), respectively. Planned comparisons of the interference effects between the 100%-frequency and 50%-frequency groups supported the results of the ANOVA above (i.e., significant interaction between frequency of occurrence and presence of AS): ASs caused greater interference in the 50%-frequency than in the 100%-frequency group for both target-present [$t(18) = 3.15$, $p < .015$] and target-absent [$t(18) = 3.3$, $p < .014$] trials.

In order to exclude the possibility that the sheer amount of (i.e., experience with) AS trials was responsible for the reduced interference in the 100% group, in which observers encountered double the number of ASs, as compared with the 50% group, we carried out a control experiment in which, after two blocks of 60 trials with no AS (0%-AS condition), one half of the observers performed one block of 60 trials with 100% ASs, and the other half performed two blocks of 60 trials with 50% ASs. In this way, each observer encountered the same number of AS trials, regardless of the group to which she/he was assigned. The results replicated those of Experiment 1, with greater interference from ASs in the 50%-AS condition (54 msec) than in the 100%-AS condition (18 msec) and greater interference for target-absent (41 msec) than for target-present (25 msec) trials. These results were confirmed by an ANOVA with the between-subjects factor frequency (50% vs. 100%) and the within-subjects factors target presence (present vs. absent) and AS presence (present vs. absent). It is important that the main effect of AS was significant [$F(1,15) = 17$, $p < .001$] and interacted significantly with both frequency [$F(1,15) = 4.9$, $p < .03$] and target presence [$F(1,15) = 5.8$, $p < .03$]. Thus, it is safe to conclude that the strength of interference from ASs was dependent on their frequency of occurrence, rather than on their sheer number. This is consistent with Müller et al. (2009), who interpreted the frequency of ASs to influence observers' incentive to operate an effortful top-down suppression strategy.

Further analyses of the 50%-frequency group. In the previous analysis, AS-absent trials from the interference condition of the 50%-frequency group had been omitted. In the following analysis, these trials were used to calculate the interference effect in an alternative fashion: Instead of comparing AS trials from the interference condition with no-AS trials from the control condition, we assessed interference by comparing AS trials from the interference condition with no-AS trials also taken from the interference condition (because this condition consisted of both trials with and trials without an AS in the 50%-frequency group). An ANOVA with the between-subjects factor order (control condition first vs. second) and the within-subjects factors target presence (present vs. absent) and AS presence (present vs. absent, both from the interference condition) revealed main effects of target presence [$F(1,8) = 17.6, p < .003$] and AS presence [$F(1,8) = 33.7, p < .001$] and showed the interaction between target presence and AS presence [$F(1,8) = 26.3, p < .001$] to be significant (Figure 2). Planned comparisons revealed the distracting effect of the AS to be significant for both target-present trials [21 msec; $t(9) = 3.2, p < .02$] and target-absent trials [52 msec; $t(9) = 7.7, p < .001$].

For the 50%-frequency group, another comparison is of interest: Is RT performance in the absence of an AS in any way dependent on the probability of an AS occurring on a given trial? In the control (0%-frequency) condition, an AS never occurred, whereas in the interference condition, an AS could have occurred in half of the trials. An ANOVA of RTs on singleton-absent trials with the factors target presence (absent vs. present) and experimental condition (interference vs. control) revealed both main effects—target presence [$F(1,8) = 5.7, p < .04$] and experimental condition [$F(1,8) = 5.6, p < .05$]—to be significant. The latter effect was due to RTs being slower when an AS could potentially have occurred than when an AS could never occur (interference vs. control condition: 463 vs. 448 msec), even though the displays were physically identical in both cases.

Discussion

In Experiment 1, additional cross-dimensional singletons interfered with the detection of pop-out targets. The disrupting effect depended on two factors: frequency of occurrence and target presence. More frequent ASs resulted in a reduced interference effect, likely due to an increased incentive to suppress the irrelevant (AS-defining) dimension top-down, as had been shown previously for compound tasks (Müller et al., 2009). Specifically, when ASs occurred in 100% of the trials, target-present RTs were not significantly slowed (relative to the 0% baseline); in contrast, when an AS occurred in only 50% of the trials, discerning the presence of a target was slowed significantly, irrespective of the baseline (i.e., AS-absent trials in the 0% control or, alternatively, in the 50% interference condition). Furthermore, on target-absent trials, processing was always impaired by the presence of an AS.

The null finding of no distraction from ASs for target-present decisions in the 100%-frequency group replicates the results of Chan and Hayward (2009) and Kumada (1999). However, if their dual-route hypothesis were true, ASs would not be expected to disrupt processing either in the 50%-frequency group or on target-absent trials.

For the question at issue, the most important result of Experiment 1 is the finding of interference from ASs in a detection task, with the magnitude of interference being dependent on the frequency with which ASs occur (which had already been shown to be important for compound tasks by Müller et al., 2009). This pattern is consistent with the assumption that both detection and compound tasks are processed via the same route, one that is prone to interference effects, and it is at variance with the assumption that detection tasks are processed via a special route that is, in principle, immune to interference (as proposed by the dual-route models).

Additional evidence for the assumption that detection and compound tasks share the same processing route derives from an intertrial analysis analogous to that applied by Müller et al. (2009) to their compound-task data. Müller et al. (2009) found that, with low frequencies of AS, their interference effect depended on presence of an AS in the preceding trial: Interference was larger if on the preceding trial an AS was absent rather than present. In line with Botvinick, Braver, Barch, Carter, and Cohen (2001), Müller et al. (2009) proposed that the presence of an unexpected (rare) AS invokes cognitive-control processes that lead to a short-lived down-modulation of the weight assigned to the irrelevant dimension, resulting in reduced interference after AS trials. However, since this top-down set is not maintained consistently over runs of (frequent) trials without an AS, the appearance of the next AS is likely to again cause interference. In order to verify that the same mechanisms are at work in the present detection task, the size of interference effects for the 50%-frequency group of Experiment 1 was reanalyzed dependent on the intertrial history; the 100%-frequency condition could not be examined in this way because an AS was present on each trial. An ANOVA of the size of the interference on trial n revealed a significant main effect of the presence of an AS on trial $n-1$ [$F(1,9) = 8.8, p < .02$], with greater interference after trials that did not contain an AS than after trials that did (51 vs. 20 msec, respectively, with target-only trials from the 50%-AS condition as baseline). This strengthens the evidence that the same (intertrial) mechanisms are at work in modulating the interference from ASs in detection and compound tasks.

EXPERIMENT 2

The results of Experiment 1 showed that feature singletons are unlikely to be detected in the way envisaged by dual-route models (Chan & Hayward, 2009; Kumada, 1999). In order to strengthen the evidence for single-route accounts, Experiment 2 examined the effect of manipulating the salience of cross-dimensional ASs relative to that of the target. Again, as with the manipulation of AS frequency in Experiment 1, dual-route accounts predict no interference at all, whereas one-route models predict interference to be larger the higher the relative saliency of additional singletons. In addition, Experiment 2 was meant to show that any effect of the relative saliency of cross-dimensional ASs in detection tasks is independent of the specific target- and singleton-defining dimensions, as had already been shown for compound tasks (e.g., Theeuwes, 1992). Thus, the AS introduced in Experiment 2 could be either more or less salient than the targets. To generalize the finding of interference in detection tasks to other dimensions, the dimensions *luminance* and *orientation* were used in Experiment 2 (instead of *color* and *orientation* in Experiment 1), with the roles of target- and singleton-defining dimensions exchanged between Experiments 2A and 2B (targets were orientation defined and AS-luminance defined in Experiment 2A and vice versa in Experiment 2B; see Table 2).

Method

Participants. Twenty-four observers (16 female, 1 left-handed) with a median age of 24 years participated in Experiment 2, with 12 observers assigned to Experiment 2A and 12 to Experiment 2B, respectively. Participants were recruited from the University of Munich student population.

Apparatus and Stimuli. For Experiments 2A and 2B, the apparatus was the same as that used in Experiment 1. The physical properties of the stimuli were the same in Experiments 2A and 2B. Distractors were 34 gray bars (1.3º high, 0.3º wide) tilted 45º to the left and a luminance of 5 cd/m^2. The bars were arranged on three (invisible) circles of a radius of 4.5º, 8.5º, and 12.5º of visual angle around a 0.2º white fixation spot. The inner, middle, and outer circles consisted of 6, 12, and 16 items, respectively. Targets could appear only at positions of the middle circle.

In Experiment 2A, targets were tilted 45º to the right from vertical (i.e., defined by a 90º orientation contrast to the left-tilted distractors). ASs were bars that were brighter than the distractors, with either weak (15 cd/m^2) or strong (90 cd/m^2) luminance contrast. In Experiment 2B, the dimensions of target and irrelevant singletons were reversed. Targets were light gray (25 cd/m^2), and ASs were tilted 32º to the left (weak feature contrast) or 45º to the right (strong feature contrast). The resulting feature contrasts of the targets and of the weak and strong ASs relative to the distractor items are listed in Table 2.

These target and AS settings were chosen on the basis of the findings of a pilot experiment that was designed to ensure that the weak and strong AS features would produce significantly slower and faster RTs, respectively, than the relevant target features. Furthermore, an additional set-size experiment with 10 observers was carried out to verify that targets even more similar to distractors in orientation (tilted 35º to the left, as compared with 32º in the present study) and luminance (11 cd/m^2 luminance, as compared with 15 cd/m^2 in the present study) would still be detected efficiently (i.e., slopes less than 5 msec/item). In this control experiment, targets were defined by either luminance or orientation with either a high (90 cd/m^2 or tilted 45º to the right) or a low (11 cd/m^2 or tilted 35º to the left) feature contrast, relative to the distractors (5 cd/m^2 and tilted 45º to the left). Observers were presented with displays with either 19 possible target positions, as in Experiment 2, or with only 7 possible positions. Set size was reduced in the latter condition by removing the outer ring of stimuli, and targets could occur only at the positions of the inner circle or the central position of the search array (yielding 7 possible target locations). In order to keep the density of the stimuli constant across the two set-size conditions, while at the same time keeping the positional probability of target occurrence constant, the low-set-size array could be presented centered at any of 6 equidistant positions 4.5º around the midpoint of the screen. Although there was a significant set-size effect [$F(1,9) = 7.4$, $p < .02$], all search slopes were well below 4 msec/item [all $ts(9) < -4$, $ps < .02$]; that is, on standard criteria (e.g., Wolfe, 1994), search remained efficient, even with targets that were less salient than those used in Experiment 2.

Design and Procedure. In Experiment 2, the target- and AS-defining dimensions were varied. In Experiment 2A, the target dimension was orientation and the AS dimension luminance; this was reversed in Experiment 2B. The target-present:target-absent trials ratio was 1:1. Independent of target presence, an AS was presented in 50% of the trials. Half of the ASs were of high saliency, and half were of low saliency. The timing of events on a trial was the same as in Experiment 1. Each part of Experiments 2A and 2B consisted of 18 blocks of 60 trials each, giving a total of 1,080 trials.

Table 2
Feature Contrasts (Rather Than Absolute Feature Values) of the Targets and of the Weak and Strong Additional Singletons (ASs), Relative to the Distractors

Stimulus	Experiment 2A	Experiment 2B
Target	90º	20 cd/m^2
Weak AS	10 cd/m^2	13º
Strong AS	85 cd/m^2	90º

Note—Distractors comprised 45º left-tilted dark gray (5 cd/m^2) bars for the luminance dimension and in degrees of tilt from the vertical for the orientation dimension.

Results and Discussion

Trials with RTs shorter than 200 msec or longer than 1,200 msec were excluded from RT analysis (fewer than 1.6% of all trials), as were response error trials (3.0% overall).

An ANOVA of the error rates with the between-subjects factor of experiment (2A or 2B) and the within-subjects factors of target (present or absent) and AS (absent, strong, or weak) revealed the main effect of AS [$F(2,44) = 6.8$, $p < .003$] and the interaction between target and AS [$F(2,44) = 14.6$, $p < .001$] to be significant. The factor of experiment was nonsignificant ($F < .05$, $p > .5$) and did not interact with any other factor(s): For experiment × target, $F < 1.2$, $p > .28$; for experiment × AS, $F(2,44) = 2.0$, $p > .14$; for experiment × target × AS, $F < 0.01$, $p > .97$. In order to examine the target × AS interaction, separate ANOVAs were carried out for target-present and target-absent trials. For target-present trials, there was no significant effect (error rates were 3.9%, 3.0%, and 3.1% for absent, weak, and strong ASs, respectively). For target-absent trials, the main effect of AS was significant [$F(2,44) = 13.8$, $p < .001$]: Error rates increased from trials without ASs (0.6%) through trials with weak ASs (2.9%) to trials with strong ASs (5.1%); a Tukey's HSD test revealed that all factor levels differed significantly from each other (all $ps < .03$).

The RT data for Experiments 2A and 2B are presented in Figure 3. An ANOVA of the RTs (with a design analogous to that of the overall error rates) yielded significant main effects of AS [$F(2,44) = 108.6$, $p < .001$]. Experiment did not interact with target [$F(1,22) = 3.3$, $p < .08$], AS [$F(2,44) = 1.2$, $p < .31$], or target and AS ($F < 0.13$, $p < .9$).

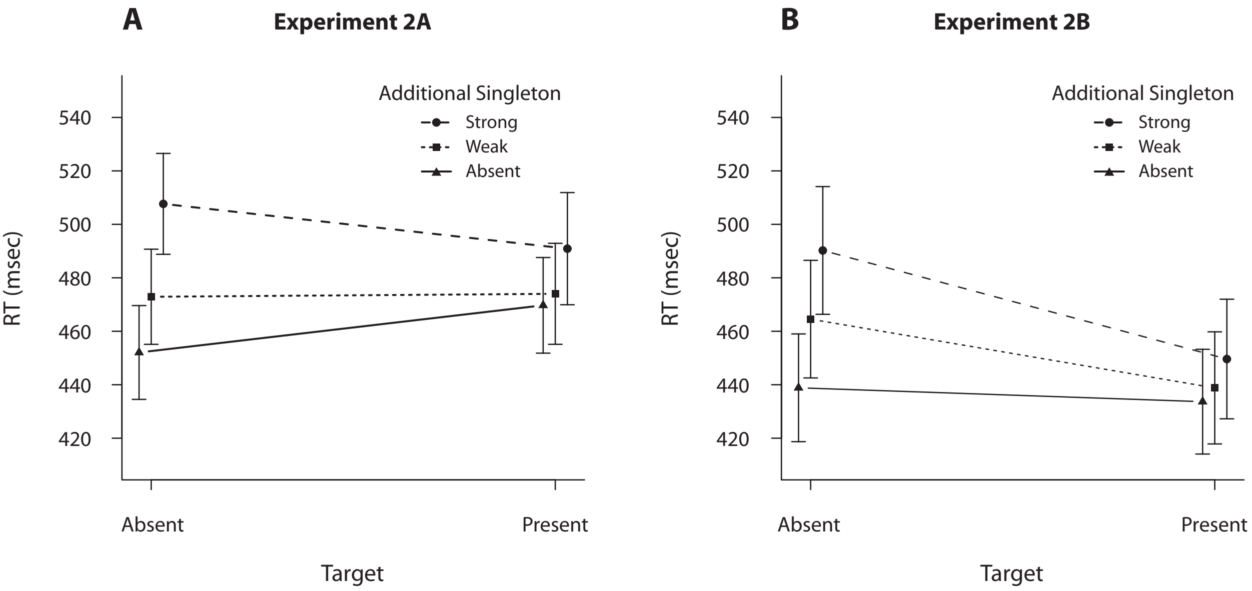

Figure 3. Mean reaction times (RTs, in milliseconds), as a function of target presence and AS presence/strength in Experiments 2A (panel A) and 2B (panel B). Bars represent standard errors of the means.

The significant interaction between target and AS [$F(2,44) = 36.8, p < .001$] was explored further in ANOVAs carried out separately for target-present and target-absent RTs. For target-present RTs, again there was a significant main effect of AS [$F(2,44) = 21.9, p < .001$], with slower RTs for strong ASs than for absent ASs (470 vs. 452 msec; Tukey's HSD, $p < .001$) and weak ASs (470 vs. 456 msec, $p < .001$). Given the error results, this pattern of RT effects is unlikely to be contaminated by a speed–accuracy trade-off. For target-absent trials, the main effect of AS was also significant [$F(2,44) = 119, p < .001$], with RTs of 446, 468, and 499 msec for absent, weak, and strong ASs, respectively. A Tukey's HSD test revealed that all three factor levels differed significantly from each other (all ps $< .001$). In the analysis of both target-present and target-absent RTs, experiment was nonsignificant and did not interact with presence of AS (all Fs < 1).

In summary, using a detection task, Experiment 2 showed the specific target- and AS-defining dimensions to be irrelevant. The only determinant of AS interference was relative saliency. It is important that Experiment 2 replicated the interference from ASs from Experiment 1 (see Table 3 for a summary of the interference effects). The mean interference effect was 25 msec. As in Experiment 1, target-absent decisions were more strongly affected by the presence (rather than by the absence) of an AS than target-present decisions were (38 msec vs. 11 msec). Furthermore, the saliency level of the AS (relative to that of the target) modulated the AS interference effect: 14 msec and 36 msec for weak and strong ASs, respectively.

EXPERIMENT 3

The findings of Experiments 1 and 2 falsify two of the core assumptions made by dual-route models: Assumption 1 states that detection tasks are solved via a special, nonspatial (nonsaliency map) route, and Assumption 2 states that this route is immune to cross-dimensional interference: Detection decisions can be based on one of several dimensionally segregated modules, disregarding evidence from other dimensions. In order to account for small cross-dimensional interference effects in detection tasks, Chan and Hayward (2009) proposed an ad hoc modification of the original notion of dimensional modules derived from FIT (Treisman & Gormican, 1988) that could, in principle, accommodate interference from cross-dimensional ASs in detection tasks. In essence, they dropped Assumption 2, assuming instead that some sort of dimension-specific attention might be diverted from the to-be-monitored target module to the to-be-ignored AS module (which accumulates singleton information faster). However, they clearly maintain core Assumption 3—namely, that the detection route, in contrast to the salience map route, is spatially nonspecific: "Capture for simple tasks is nonspatial" in nature (Chan & Hayward, 2009, p. 131). Accordingly, the distance between the target and the AS should have no modulatory effect on the interference. By contrast, single-route models, which assume that ASs and targets compete for focal–attentional selection at the level of the salience (master) map, could accommodate spatial modulations of the interference effect. Indeed, such modulations (like those found by Theeuwes & Hickey, 2008, in a compound task) are potentially diagnostic of spatial interactions within the saliency map.

To examine the differential predictions relating to distance effects, the spatial distance between targets and ASs was systematically varied in Experiment 3. The distances tested were 1 (*immediately neighboring*), 2 (*one distractor item in between*), 3, or 5. Since Theeuwes and Hickey (2008) had also reported a hemifield effect for their compound-task data (i.e., a reduced distance effect

Table 3
Interference From Additional Singletons in Experiment 2

	Relative Saliency (msec)	
Target	Weak	Strong
Present	4	18
Absent	23	53

Note—Interference was calculated relative to trials in which no AS was present. Effects were combined across Experiments 2A and 2B.

for an AS located in a different hemifield from the target), whether target and AS were presented in the same or in different hemifields was also explicitly manipulated in Experiment 3. The dual-route account predicts no effect of distance on the size of the interference effect, because dimension modules provide only nonspatial signals. By contrast, the single-route account can easily accommodate distance effects, because it assumes that—for detection tasks, as well—interference arises as a result of interactions within the salience map, which is inherently spatial.

Method

Participants. Fourteen observers (10 female, median age = 24 years) participated in Experiment 3.

Apparatus and Stimuli. The apparatus was the same as that used in Experiments 1 and 2. The stimuli were the same in size and arrangement as in Experiment 2, with two differences. First, distractor items were of a slightly darker shade of gray (4 cd/m^2), in order to increase the relative salience of the luminance-defined AS, and targets were defined in the orientation dimension (tilted 20º randomly to the left or the right) among vertical distractor items. Second, the whole stimulus display was rotated 15º in order to avoid presenting targets or distractors exactly on the vertical meridian.

The distances between the target and the AS (on trials in which both were present) were manipulated according to the following algorithm: First, the target was placed randomly at one of the 12 possible positions arranged equidistant to the center of the screen. Then the AS was placed at a position randomly shifted 1, 2, 3, or 5 positions to the left or right of the target in the circular arrangement.

Design and Procedure. The experiment consisted of 19 blocks of 72 trials each. The target-present:target-absent trials ratio was 1:1. Independent of target presence, an AS was presented in 50% of the trials.

Results and Discussion

The data were examined in a two-stage process. First, the error and RT data were examined by an ANOVA with factors of target (absent vs. present) and AS (absent vs. present); this was followed by an ANOVA of the size of the (RT) interference effect for the target-present condition with factors of distance (1, 2, 3, or 5) and hemifield (*same* vs. *different*).

The target × AS ANOVA of the error rates revealed both main effects to be significant: More misses were made than false alarms [3.8% vs. 2.1%; $F(1,13) = 11.1$, $p < .005$], and, overall, more errors were made when an AS was present [3.6% vs. 2.3%; $F(1,13) = 6.7$, $p < .02$]. The latter effect was more pronounced for target-absent trials (3.5% vs. 0.8%) than for target-present trials (3.8% vs. 3.8%), as evidenced by a significant target × AS interaction [$F(1,13) = 9.8$, $p < .008$].

An analogous ANOVA of the RTs revealed a main effect of AS [$F(1,13) = 60$, $p < .001$], which interacted with target presence [$F(1,13) = 46$, $p < .001$]. ASs slowed RTs by 32 msec on target-absent trials, but only by 8.5 msec on target-present trials. Planned *t* tests confirmed that the interference was significantly greater than 0 for both target-absent [$t(13) = 11.8$, $p < .002$] and target-present [$t(13) = 2.6$, $p < .02$] trials.

The size of interference effect for the factors of distance and hemifield is presented in Figure 4. An ANOVA on the size of AS–RT interference (on target-present trials) with the factors of distance between target and AS (1, 2, 3, or 5) and hemifield (*same* vs. *different*) revealed the main effect of distance to be significant [$F(3,39) = 3.1$, $p < .04$], and that of hemifield approached significance [$F(1,13) = 4.5$, $p < .053$]; the interaction between both factors was nonsignificant [$F(1,13) = 0.6$, $p < .58$]. That is, the interference effect was larger for close than for far distances and tended to be larger for ASs presented in a different, rather than in the same, hemifield relative to the target (7.5 vs. 9.5 msec). The latter finding differs from that of Theeuwes and Hickey (2008), who reported larger interference for same-hemifield ASs.

Judging from Figure 4, although the interaction was nonsignificant, the greater overall interference from different-hemifield ASs clearly derives from distances larger than 1. It may be that, with small distances between the target and the AS, both stimuli (located near the vertical meridian) are coded in both hemispheric salience maps. As a result, a strong competition between the two hemispheres would arise only with larger separations, in which case a spatially clearly separate AS in one hemifield could summon attention somewhat more effectively and thus cause greater interference; the increased interference may then arise also because visuospatial attention would have to be reoriented from the AS across the vertical meridian to the target. However, especially given that Theeuwes and Hickey (2008)

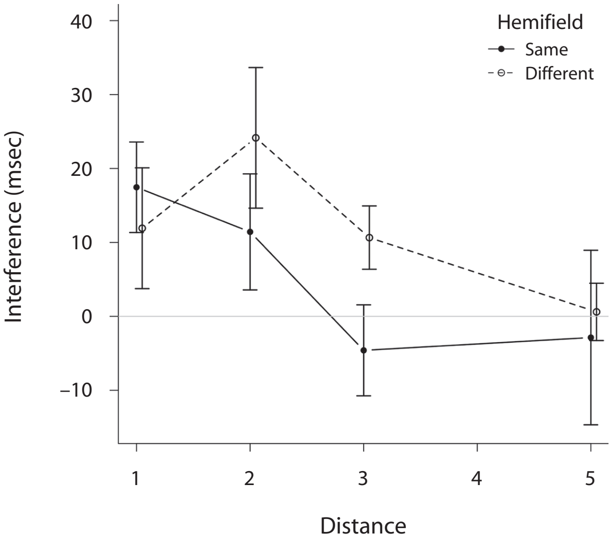

Figure 4. Mean size of the interference effect on response times (RTs, in milliseconds), as a function of the distance between the target and the additional singleton, separately for singletons in the *same* and *different* hemifields. Bars represent standard errors of the means.

found a different pattern of hemifield effects, further work is required in order to clarify the hemifield modulation of the distance effect. Nevertheless, the finding of any spatial modulations of the interference effect in the present detection task, although being in accordance with single-route accounts, is difficult to reconcile with Assumption 3, the nonspatiality of AS interference (see Chan & Hayward, 2009) of dual-route accounts.

GENERAL DISCUSSION

The present study was designed to test core assumptions of dual-route models (Chan & Hayward, 2009; Kumada, 1999; FIT, Treisman, 1988)—namely, Assumption 1, which states that detection tasks are solved via a special, dimensionally segregated route (that somehow bypasses the salience map); Assumption 2, which states that this route is free of cross-dimensional interference; and Assumption 3, which operates in a spatially nonspecific manner. By contrast, single-route models, such as DWA (Müller et al., 1995) and GS (Wolfe, 1994), assume that a saliency map is involved in the processing of nonspatial (e.g., detection) and spatial (e.g., compound) tasks. Experiments 1 and 2 introduced manipulations known to modulate the magnitude of the interference effect in compound tasks.

In Experiment 1, we replicated the absence of cross-dimensional AS interference for target-present trials when we compared trial blocks of 100% AS presence with blocks of 0% presence. However, when we reduced the AS frequency to 50%, performance on target-present trials was slower when an AS was present. This pattern, which is qualitatively the same as that observed in compound tasks, contradicts Assumption 2 of the dual-route models.

Likewise, Experiment 2 demonstrated that, when the salience of the AS is increased relative to that of the target, cross-dimensional ASs come to produce interference in a detection task. Again, this pattern is qualitatively similar to that observed in compound tasks and contradicts Assumption 2 of the dual-route models.

Finally, Experiment 3 revealed AS interference in detection tasks to be modulated by the spatial separation of the AS from the target—a finding at variance with Assumption 3 of the dual-route models or, alternatively, the auxiliary assumption introduced by Chan and Hayward (2009) (i.e., the nonspatiality of AS interference).

Taken together, this set of results supports single-route models, according to which task performance is mediated by one spatial processing route—that is, computation of a topographic saliency map based on weighted dimension-specific feature contrast signals—in both detection and compound/localization tasks.

Blocking ASs Can Confound Estimation of Interference

Irrespective of whether or not detection is processed via the salience map in the same way as compound and localization tasks, the present study also points to a methodological confound that can lead to an overestimation of AS interference when singleton presence is manipulated in pure trial blocks (100% vs. 0%). In Experiment 1, RTs for displays containing only a target (i.e., without any ASs) were affected by the probability with which an AS could occur. Target-present responses were faster in blocks in which no ASs occurred at all than in blocks in which ASs could occur. Consequently, when estimating the AS interference effect by subtracting RTs on target-only trials in the 0%-AS condition from RTs on target-plus-AS trials in the 100%-AS condition, the result confounds the interference effect with the general slowing in response speed when ASs can be present. This may be illustrated by looking at a numerical example from the 50% group of Experiment 1. In the control condition (blocks without any ASs), target-present responses took 430 msec, whereas responses for target-present trials without an AS in the interference condition (blocks with an AS in 50% of the trials) took 450 msec. In the latter condition, target-present RTs on trials with an AS in the display were 470 msec. If the AS interference effect is calculated by comparing AS trials (50%-AS condition) with the control trials (0%-AS condition), as is usual for 100%-AS conditions (e.g., Theeuwes, 1992), it would amount to 40 msec, which is twice as much as the 20 msec estimated by comparing AS and no-AS trials within the same experimental condition.

At first glance, these considerations suggest that the blocked 0%-AS baseline leads to a larger estimate of the interference effect than a mixed baseline does. We argue that this larger value is, in fact, an overestimate, and the mixed baseline is preferable in both detection and compound tasks. If ASs can never occur in a display (0%-AS condition), processing may differ qualitatively from that of target-only displays in a mixed condition. In the latter, target identity has to be determined, whereas this additional process can be omitted in target-only blocks. In mixed blocks (with unpredictable occurrences of ASs), strategies, criteria, and the set processing stages involved are similar on both target-only and AS trials, the only difference being the (possible) presence of an AS. Given this, it is recommended to calculate AS interference by comparing RTs with and without ASs obtained within the same blocks of trials (i.e., blocks in which AS frequency is less than 100%).

Note that there are findings reported in the literature for which this baseline issue may be particularly relevant. For instance, Lamy and Yashar (2008) compared the interference effect in a compound task between a condition with a 50% frequency of AS and one with a 100% frequency of AS (the latter was compared with a 0% frequency of AS baseline). Müller et al. (2009) would predict less interference in the 100%- to 0%-AS condition than in the 50%-AS condition. However, Lamy and Yashar found the interference effect to be comparable in magnitude between both conditions. In light of the present study, the reason for this finding might be the fact that the baseline target-only trials were mixed with AS trials in Lamy and Yashar's 50%-AS condition, whereas they were presented in blocked fashion in their 100%-AS condition. Therefore, the estimate of the interference effect is systematically larger in the 100%-AS than in the 50%-AS condition (twice as large in the present study). The pattern might change in a comparison made between a 50%-AS and, say, a 90%-AS condition, where the no-singleton trials for calculating the interference effect could be taken from the same (respective) blocks as the singleton trials. A similar argument could be made for Experiment 1 of Bacon and Egeth (1994), who in their discussion also reported interference effects of a 50%-AS and a 100%-AS condition to be comparable.

Outlook

The present study strengthens the view that one-route models, such as GS (Wolfe, 1994) and DWA (Müller et al., 1995), provide a better description of the processing architecture in spatial and nonspatial tasks than do dual-route models (Chan & Hayward, 2009; Kumada, 1999; Treisman & Gormican, 1988). However, the question remains why interference from AS is smaller for detection tasks than for compound and localization tasks (Chan & Hayward, 2009). Even though one-route models imply that the weighted saliency map is involved in both nonspatial and spatial tasks, processing has to diverge at some point in order to fulfill the different task requirements. In compound tasks, activity on the saliency map controls the deployment of spatial attention, whereas in detection tasks, it is sufficient to determine whether a strong feature contrast signal is present. Presumably, the quantitatively different AS effect between the two types of tasks has its source after this divergence, but the exact nature of this source remains to be determined in future research.

AUTHOR NOTE

The authors thank Jeremy Wolfe, Louis Chan, and Dominique Lamy for valuable comments on earlier versions of this article. This research was supported by the following grants: DFG Excellence Cluster Grant EC 142 "CoTeSys" to H.J.M. and M.Z.; and DFG Research Group Grant FOR480 to H.J.M. Correspondence concerning this article should be addressed to M. Zehetleitner, LMU Department Psychologie, Leopoldstr. 13, 80802 München (e-mail: mzehetleitner@psy.lmu.de).

REFERENCES

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, **55**, 485-496.

Becker, S. I. (2007). Irrelevant singletons in pop-out search: Attentional capture or filtering costs? *Journal of Experimental Psychology: Human Perception & Performance*, **33**, 764-787. doi:10.1037/0096-1523.33.4.764

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. C. (2001). Conflict monitoring and cognitive control. *Psychological Review*, **108**, 624-652. doi:10.1037/0033-295X.108.3.624

Bravo, M. J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception & Psychophysics*, **51**, 465-472.

Chan, L. K. H., & Hayward, W. G. (2009). Feature integration theory revisited: Dissociating feature detection and attentional guidance in visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **35**, 119-132. doi:10.1037/0096-1523.35.1.119

Duncan, J. (1985). Visual search and visual attention. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI: Attention and neuropsychology* (pp. 85-104). Hillsdale, NJ: Erlbaum.

Fecteau, J. H. (2007). Priming of pop-out depends upon the current goals of observers. *Journal of Vision*, **7**, 1-11. doi:10.1167/7.6.1

Folk, C. L., & Remington, R. [W.] (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception & Performance*, **24**, 847-858. doi:10.1037/0096-1523.24.3.847

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception & Performance*, **18**, 1030-1044. doi:10.1037/0096-1523.18.4.1030

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a "dimension-weighting" account. *Perception & Psychophysics*, **58**, 88-101.

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, **40**, 1489-1506. doi:10.1016/S0042-6989(99)00163-7

Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology*, **4**, 219-227.

Kumada, T. (1999). Limitations in attending to a feature value for overriding stimulus-driven interference. *Perception & Psychophysics*, **61**, 61-79.

Lamy, D., Tsal, Y., & Egeth, H. E. (2003). Does a salient distractor capture attention early in processing? *Psychonomic Bulletin & Review*, **10**, 621-629.

Lamy, D., & Yashar, A. (2008). Intertrial target-feature changes do not lead to more distraction by singletons: Target uncertainty does. *Vision Research*, **48**, 1274-1279. doi:10.1016/j.visres.2008.02.021

Müller, H. J., Geyer, T., Zehetleitner, M., & Krummenacher, J. (2009). Attentional capture by salient color singleton distractors is modulated by top-down dimensional set. *Journal of Experimental Psychology: Human Perception & Performance*, **35**, 1-16. doi:10.1037/0096-1523.35.1.1

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, **57**, 1-17.

Proulx, M. J., & Egeth, H. E. (2006). Target–nontarget similarity modulates stimulus-driven control in visual search. *Psychonomic Bulletin & Review*, **13**, 524-529.

Proulx, M. J., & Egeth, H. E. (2008). Biased competition and visual search: The role of luminance and size contrast. *Psychological Research*, **72**, 106-113. doi:10.1007/s00426-006-0077-z

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics*, **50**, 184-193.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, **51**, 599-606.

Theeuwes, J., & Hickey, C. (2008, November). *A biased competition account of attentional capture*. Paper presented at the 49th Annual Meeting of the Psychonomic Society, Chicago.

Treisman, A. [M.] (1988). Features and objects: The Fourteenth Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology*, **40A**, 201-237.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136. doi:10.1016/0010-0285(80)90005-5

Treisman, A. [M.], & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, **95**, 15-48. doi:10.1037/0033-295X.95.1.15

Treisman, A. [M.], & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 459-478. doi:10.1037/0096-1523.16.3.459

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549-586). Cambridge, MA: MIT Press.

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

Wolfe, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, **1**, 202-238.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 95-107. doi:10.1037/0096-1523.20.1.95

(Manuscript received January 15, 2009;
revision accepted for publication July 6, 2009.)