Dimensional weighting in cross-dimensional singleton conjunction search

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In order to efficiently deploy our limited visual processing resources, we must decide what information is relevant and to be prioritized and what information should rather be ignored. To detect visual information that we know is relevant but that is not very salient, we need to set our system to prioritize and combine information from different visual dimensions (e.g., size, color, motion). Four experiments examined the allocation of processing resources across different visual dimensions when observers searched for a singleton target defined by a conjunction of size (primary dimension: the target was always large) with either color or motion (secondary dimension: variable across trials) within heterogeneously sized, colored, and moving distractors. The results revealed search reaction times to be substantially increased in a given trial in which the secondary target dimension was changed from the preceding trial—indicative of a suboptimal distribution of dimensional weights carried over from the previous trial and of attentional weight being bound by the (need to filter within the) primary dimension, thereby reducing the weight available for processing the secondary dimensions. Semantic precueing of the secondary dimension and visual marking of the search-irrelevant items in the primary dimension reduced these costs significantly. However, observers were limited in their ability to implement both top-down sets simultaneously. These findings argue in favor of a parallel distribution of dimensional processing resources across multiple visual dimensions and, furthermore, that visual marking releases attentional weight bound to the primary dimension, thus permitting more efficient (parallel) processing in the secondary dimensions.

Introduction

At any given moment, the amount of visual information available in the environment exceeds the processing capacities of the visual system. Hence, the perceptual system needs to decide on what information is to be selected for deeper and more explicit processing and what information is to be ignored. This decision is made on the basis of stimulus properties (stimulus-driven selection) and/or the internal "set" of the observer (top-down controlled selection). Stimuli that differ from their surround in one or more basic visual features (e.g., color contrast: a red item among green items or orientation contrast: a right-tilted bar among left-tilted bars) attract visual attention in a more or less automatic fashion. Such stimuli can be rapidly discerned, irrespective of the number of items in the field (the display size); phenomenally, they appear to "pop out" of the display. A number of feature dimensions have been shown to support such a spatially parallel (i.e., display size–independent) search, including orientation, size, color, motion, and stereo depth. Although computation of feature contrast within a given dimension proceeds largely automatically (e.g., by suppressive interactions among like-feature suppression within low-level feature maps; Li, 1999), there is evidence target selection is based on a higher-level representation: a "featureless" overall-saliency map of the visual field the units which integrate (i.e., sum) the local feature contrast signals computed in different dimensions (e.g., Krummenacher, Müller, & Heller, 2001, 2002; Wolfe, 1994; Zhaoping & May, 2007). Furthermore, there is evidence that not all dimensions contribute equally to the (integrated) overall-saliency

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signals; rather, feature contrast signals from dimensions that are more "relevant" will have a stronger impact or "weight" in the integration process. For instance, a feature dimension that supports successful target detection in a given trial is implicitly assumed to be more important in the future; accordingly, the weight assigned to feature contrast signals from this dimension is increased while the weights for other dimensions are correspondingly decreased (Found & Müller, 1996; Müller, Heller, & Ziegler, 1995). According to this "dimension-weighting account" (DWA) of visual search for singleton feature targets (e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995), the greater the weight assigned to the target dimension, the greater the rate at which evidence for a target actually defined within this dimension accumulates at the overall-saliency level and, accordingly, the faster the target can be detected. The (cross-dimensional) weight pattern established in a given trial persists into the next trial. This ensures fast and efficient target detection if the target-defining dimension is repeated across consecutive trials. In contrast, if the target-defining dimensions change across trials, target detection is slowed. These reaction time (RT) costs are primarily dimension-specific in nature, that is, changes of the target-defining feature across visual dimensions, as compared to changes within a given dimension, increase target detection times (Found & Müller, 1996; Müller, Heller, & Ziegler, 1995; see also the article by Rangelov, Müller, & Zehetleitner, 2013, in this Special Issue). These automatic weighting processes are also, to some extent, top-down modulable. For instance, when the target-defining dimension is cued in advance by a symbolic precue, detection of a singleton feature target is facilitated when it is defined in the cued (vs. an uncued) dimension, and the effect of a dimension change across trials is reduced compared to a neutral cueing condition (e.g., Müller, Reimann, & Krummenacher, 2003).

While dimensional weighting plays an important role in selecting salient singleton items, in everyday life relevant visual information rarely pops out from the scene. Rather, everyday visual scenes are typically heterogeneous and complex in their composition with target detection requiring the combination (or "conjunction") of feature signals from several visual dimensions. This makes search more dependent on the observer's endogenous settings, demanding greater involvement of top-down control.

For instance, search for a (singleton) target defined by a conjunction of features—such as a large red item among large green and small red items—requires the combination of information across the color and size dimensions. The need to combine signals from different dimensions has been shown to substantially increase the effects of cross-trial repetitions/changes of the target-defining dimension(s) (Weidner & Müller, 2009; Weidner, Pollmann, Müller, & von Cramon, 2002). In these studies, observers searched for singleton targets that were defined by a fixed primary dimension (size: a target was always large) and, variably across trials, a secondary dimension, which was either color or motion direction (i.e., the target was either [large and] differently colored [e.g., red rather than green], or [large and] differently moving, [sinusoidally oscillating on, e.g., a $\pm 45°$–oriented axis rather than on the horizontal axis]). Cross-trial changes of the secondary target-defining dimension (compared to repetitions of the secondary dimension) resulted in search RT costs that were three to five times larger than those observed in singleton feature searches for the same (color and, respectively, motion-defined) targets.

Assuming that these enlarged dimension-specific effects are owing to the need to combine information from different visual dimensions and, thus, to a greater demand for top-down control, these effects should be highly susceptible to "precues" providing prior knowledge about upcoming target features. Given this, the present series of four experiments was designed to examine the impact of prior top-down information regarding the primary and secondary target-defining dimensions on dimensional (cross-trial) effects in singleton conjunction search.

Observers searched for large, colored, moving squares embedded within a set of heterogeneous distractors. Target detection required a combination of features from different dimensions, namely size (primary dimension: the target was always large) with either color or motion direction (secondary dimensions: the target was either odd-colored or oscillating in an odd direction). Experiment 1 was designed to establish and replicate the differential size of dimensional intertrial effects between singleton conjunction and singleton feature search. Experiments 2, 3, and 4 aimed at testing effects of search-relevant information presented prior to target presentation. This information related either to the primary or the secondary target-defining dimension. In particular, selective weighting of the *secondary* target-defining dimension was manipulated by presenting observers with semantic precues, indicating the likely secondary dimension defining the target in the upcoming trial (Müller, Reimann, & Krummenacher, 2003; Weidner, Krummenacher, Reimann, Müller, & Fink, 2009). Prior knowledge regarding the *primary* target-defining dimension was experimentally varied by adopting a visual-marking paradigm (Watson & Humphreys, 1997). A subset of distractors (small items) was presented prior to a second subset of relevant items (large items) that contained the (large) target. This procedure permitted observers to spatially inhibit irrelevant distractors on the basis of the primary target-defining dimension.

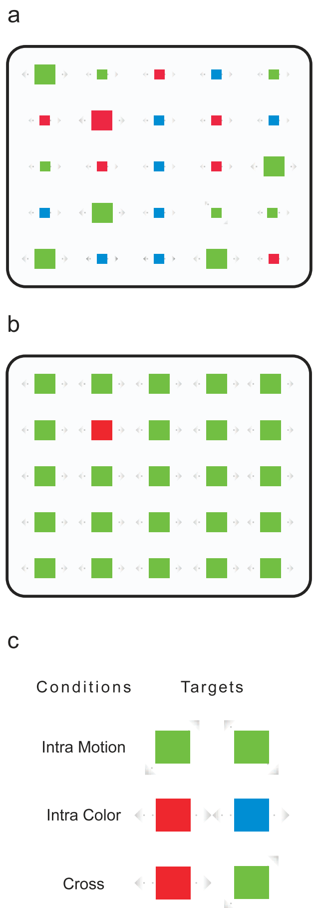

Figure 1. Example displays including a color target (a large red square) for singleton conjunction search (a) and singleton feature search (b). Note that in the experiments, item locations were spatially jittered and the sinusoidal movements were phase-shifted. Possible target configurations for the different cross-dimensional and within-dimensional search conditions (c).

Experiment 1

In order to directly compare the effects of visual dimension changes between singleton conjunction and a singleton feature search, observers performed both types of search with the same target stimuli used in both tasks. That is, in both singleton conjunction and singleton feature search, observers searched for a large filled-in square that was either red or blue or a large green square moving diagonally (Figure 1). The different types of search were induced by selectively varying the set of distractor stimuli. In singleton feature search, distractor stimuli homogeneously consisted of large filled-in squares that were green and moved (oscillated) horizontally. Each potential target stimulus thus differed from the surrounding targets in only one single feature—either color or motion direction—thus rendering the target stimulus salient and thus generating pop-out.

In contrast, distractors in singleton conjunction search were heterogeneous, consisting of stimuli that shared at least one feature with the potential target. For instance, distractor stimuli could be small and, at the same time, red or blue (i.e., sharing a color with some potential targets) or, alternatively, small and green and, at the same time, moving on a diagonal axis (i.e., sharing a motion direction with some potential targets). A target stimulus in this search condition could not be detected on the basis of simple feature contrasts; rather, target detection required the combination of information from different visual dimensions.

Because targets were identical in these singleton feature and singleton conjunction search tasks, the effects of uncertainty as to the target-defining dimension and of changes to the target definition across trials could efficiently be compared between the two conditions. To do so, the two types of search were each performed under conditions of dimension uncertainty as well as under dimension certainty. In the former condition, the secondary target-defining dimension varied across trials (cross-dimension condition); in the latter, the secondary dimension was fixed, but the target feature was variable within this dimension (intradimension condition). Changes to the secondary target-defining dimension were expected to produce greater (secondary-dimension) change costs in the singleton conjunction search task than in the singleton feature search task.

Method

Participants

Fifteen observers with ages ranging from 20 to 29 (mean age 24) years participated in Experiment 1. They were all right-handed and had normal or corrected-to-normal vision.

Stimuli and task

The observers' task was to indicate the presence of a target item in a search display consisting of 25 moving squares via left-button mouse click or, alternatively, the absence of a target via right-button click. A target was defined as being the only *large* item in the display that was either red or blue (intracolor condition) or oscillated in a direction of motion oriented +45° or −45° relative to the horizontal axis (intramotion condition) or was the only large item that was either red or moved in a direction +45° from the horizontal (cross-dimensional condition).

Two different sets of distractors were used to induce the different types of visual search.

In the *singleton feature* task, the search displays consisted of homogeneous distractor items, so as to

	Change		No change		Sum	
	RT (ms)	% misses	RT (ms)	% misses	RT (ms)	% misses
Experiment 1						
Conjunction						
Cross. motion	866	10	810	8	838	9
Cross. color	817	12	691	2	754	7
$\bar{x}$	841	11	751	5	796	8
Within motion	819	4	801	5	810	4
Within color	697	5	671	2	684	3
$\bar{x}$	758	4	736	3	747	4
Overall conjunction	800	8	743	4	772	6
Feature						
Cross. motion	495	8	463	2	479	5
Cross. color	482	2	434	1	458	1
$\bar{x}$	488	5	448	1	468	3
Within motion	449	2	438	3	444	2
Within color	436	1	427	1	431	1
$\bar{x}$	443	2	433	2	438	2
Overall feature	465	4	440	1	453	2
Overall	633	6	592	3		

Table 1. Experiment 1: Mean RTs and miss rates for color and motion targets, separately for the different search (conjunction vs. feature search), dimension uncertainty (cross-dimension vs. intradimension search), and change conditions (change vs. no change).

produce pop-out of the odd-one-out target item and were arranged in a grid-like 5 × 5 pattern. All distractor squares were large (0.6° × 0.6° of visual angle) and green and moved sinusoidally along their horizontal axis (maximum amplitude = 0.2°, speed = 1.2°/s) (Figure 1b).

In the *singleton conjunction* task, distractors were heterogeneous. Seventy-five percent of large horizontal green distractors used in the singleton feature condition were replaced by small items (0.4° × 0.4°) that were either green and moved horizontally (25%) or were red or blue (25%) and moved diagonally on an axis oriented +45° or −45° relative to the horizontal axis (25%). To avoid perceptual grouping of items moving in the same direction, some spatial jittering was introduced, and a random phase shift was added to the sinusoidal movement.

Procedure

Observers performed the singleton feature and singleton conjunction search tasks in intracolor, intramotion, and cross-dimension conditions. Observers performed these three different conditions in separate (blocked) subexperiments with 200 trials per condition. A 5-s break was included after 50 trials. The different blocks and therefore the different conditions were presented in a randomized order. Search displays contained a target item in 60% of all trials.

Data analysis

Trials were classified as (secondary-dimension) change and no-change trials depending on whether or not a target-defining feature changed across consecutive trials (from the preceding trial $n-1$ to the current trial n). Mean RTs and error (miss) rates for change and no change trials were calculated separately for the different combinations of search type (conjunction search vs. feature search), dimension uncertainty (cross-dimension search vs. intradimension search), and stimulus dimension (color vs. motion). Error trials and trials with RTs faster than 200 ms and slower than 1500 ms were excluded from RT analysis.

Results

Repeated measures ANOVAs of the RTs and error (miss) rates were performed with the factors dimension uncertainty (cross-dimension search vs. intradimension search), search type (conjunction search vs. feature search), change condition (change vs. no change), and stimulus dimension (color vs. motion). See Table 2 for the mean RTs and mean error rates.

Overall RT and error effects

Dimension uncertainty: Variability of secondary target-defining dimension affected target detection times:

Variable	RT Df	RT F score	RT p	Misses Df	Misses F score	Misses p
Dimension uncertainty	1, 14	10.67	<0.01	1, 14	7.686	<0.05
Search type	1, 14	205.8	<0.001	1, 14	9.152	<0.01
Target dimension	1, 14	48.09	<0.001	1, 14	3.263	<0.1
Change condition	1, 14	36.4	<0.001	1, 14	9.331	<0.01
Change condition × search type	1, 14	5.09	<0.05	1, 14	0.458	0.51 n.s.
Change condition × dimension uncertainty	1, 14	64.18	<0.001	1, 14	8.474	<0.05
Change condition × target dimension	1, 14	3.165	<0.1	1, 14	1.655	0.22 n.s.
Target dimension × search type	1, 14	14.71	<0.01	1, 14	0.389	0.543 n.s.
Dimension uncertainty × target dimension	1, 14	1.914	0.2 n.s.	1, 14	1.319	0.27 n.s
Dimension uncertainty × search type	1, 14	0.439	0.52 n.s.	1, 14	3.963	<0.1
Dimension uncertainty × search type × change condition	1, 14	5.66	<0.05	1, 14	0.029	0.87 n.s
Search type × dimension uncertainty × target dimension	1, 14	2.052	0.17 n.s.	1, 14	0.53	0.478 n.s.
Dimension uncertainty × target dimension × change condition	1, 14	3.749	<0.1 n.s	1, 14	0.55	0.471 n.s.
Search type × target dimension × change condition	1, 14	2.105	0.17 n.s.	1, 14	7.794	<0.05
Search type × dimension uncertainty × target dimension × change condition	1, 14	1.272	0.28 n.s.	1, 14	3.459	<0.1

Table 2. ANOVA results for Experiment 1: Four-way ANOVAs with the factors change condition (change vs. no change), secondary target dimension (color vs. motion), search type (conjunction vs. feature), and dimension uncertainty (cross-dimension vs. intradimension).

When the secondary dimension was variable across trials, RTs were significantly slower relative to when it was fixed (and only the target feature was variable in this dimension): cross-dimension search versus intra-dimensional search: 632 ms versus 592 ms; main effect of dimension uncertainty, $F(1, 14) = 10.67$, $MSE = 8871$, $p < 0.01$. The miss rates reinforced this RT effect: cross-dimensional search was associated with higher miss rates than intradimensional search, 6% versus 3%; $F(1, 14) = 7.686$, $MSE = 0.00584$, $p < 0.05$.

Search type: As can be seen from Figure 2 and Tables 1 and 2, the type of visual search had a significant effect on RTs: Observers were significantly slower in discerning target presence in singleton conjunction (772 ms) than in the singleton feature search (772 vs. 453 ms), main effect of search task, $F(1, 14) = 205.8$, $MSE = 29{,}610$, $p < 0.001$. At the same time, miss rates were greater for singleton conjunction search than for singleton feature search (6% vs. 2%), $F(1, 14) = 9.152$, $MSE = 0.00771$, $p < 0.01$), reinforcing the RT effect.

Target dimension and target dimension × search type: Color defined–targets were detected significantly faster than motion-defined targets (582 vs. 643 ms) with this difference being more marked for conjunction search (719 ms vs. 824 ms) than for feature search (444 ms vs. 461 ms), main effect of target dimension, $F(1, 14) = 48.09$, $MSE = 4{,}616$, $p < 0.001$; target dimension × search task interaction, $F(1, 14) = 14.71$, $MSE = 7{,}956$, $p < 0.01$.

Cross-trial transition effects

Classifying trials as change versus no-change trials permitted the effects of cross-trial variation in search-critical features to be examined on a trial-by-trial basis in addition to the overall cross-dimension search costs (see above). A given trial n that involved a repetition of the target feature from the preceding trial $n - 1$ was classified as a no-change trial whereas a trial n that involved a change of the target feature was classified as a change trial (see Figure 2). Change trials in the cross-dimension condition always involved changes of the secondary target-defining dimension (from color to motion direction or vice versa) whereas changes in the intradimension conditions always involved feature changes within the same primary dimension (intra-color: from red to blue or vice versa; intramotion: –45°- to +45°-oriented motion axis or vice versa). Figure 2 presents the RTs and error (miss) rates for the cross-dimensional singleton conjunction and cross-dimensional singleton feature search tasks separately for (secondary/primary) dimension change and no-change trials. Figure 2c and 2d depicts the data for color-defined targets, and Figure 2e and 2f depicts those for motion-defined targets.

Target change costs: Changes of the target definition across trials slowed target detection overall (533 ms vs. 592 ms), main effect of change condition, $F(1, 14) = 36.4$, $MSE = 2{,}740$, $p < 0.001$.

Search type modulates change costs: The RT costs induced by target changes were modulated by the type of search performed: RT costs were increased in

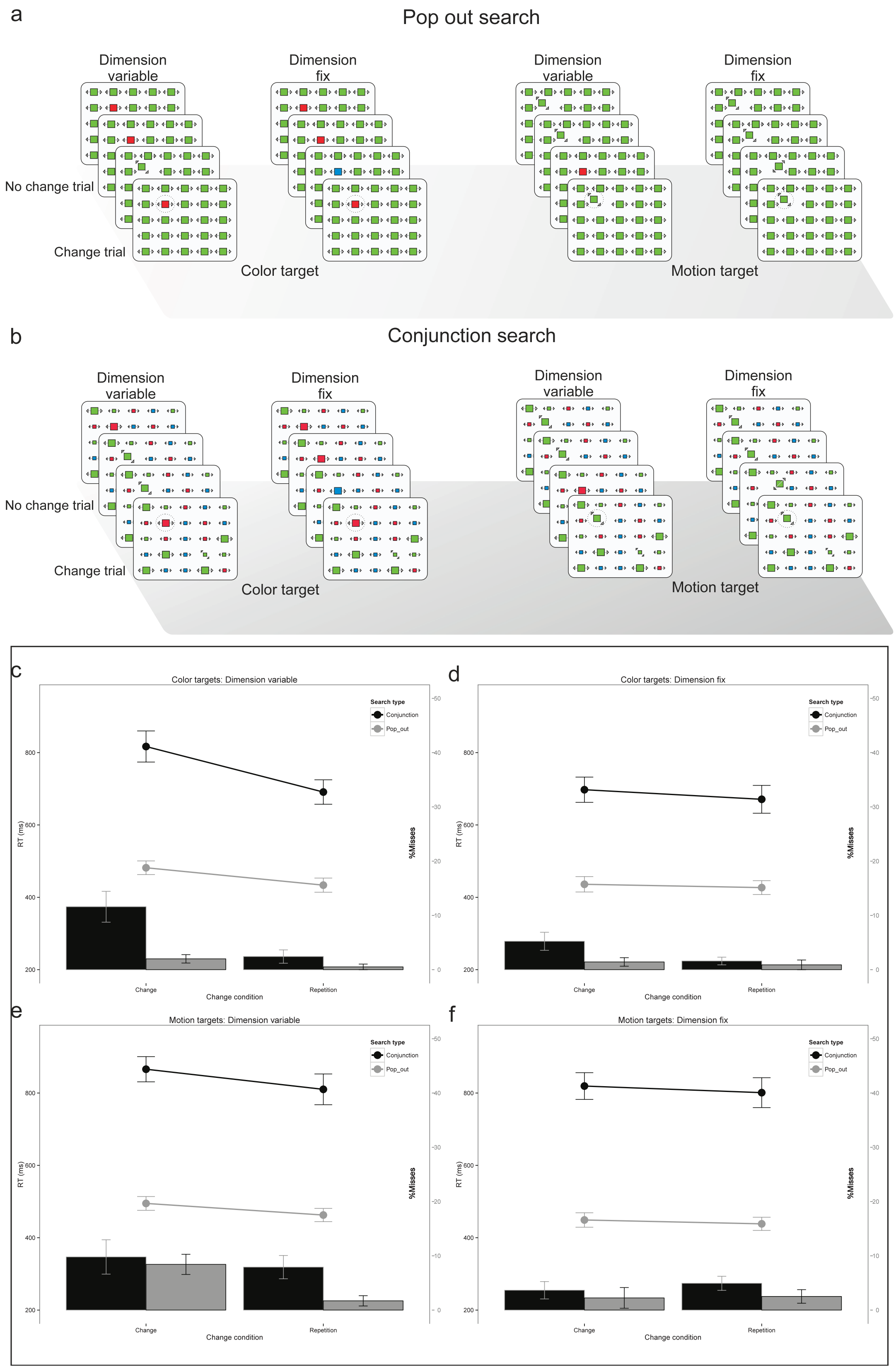

Figure 2. Sequences of sample trials from (a) the pop-out condition and (b) the conjunction search condition of Experiment 1, separately for color targets (left) and motion targets (right) with secondary target dimension either variable or fixed. (c) Reaction times (dots) and error rates (bars) for color targets in the cross-dimension conditions, separately for conjunction (black) and pop-out →

singleton conjunction search (57 ms cost: 800 ms vs. 743 ms) compared to singleton feature search (25 ms cost: 465 ms vs. 440), interaction change condition $\times$ search type, $F(1, 14) = 5.09$, $MSE = 2932$, $p < 0.05$.

Dimension uncertainty modulates change costs: Furthermore, target change costs were modulated by dimension uncertainty: In cross-dimension search, RTs were slower on dimension change than on no-change trials (665 ms vs. 599 ms); by contrast, there were no significant feature change effects in intradimension search (600 ms vs. 584 ms), interaction dimension uncertainty $\times$ change condition, $F(1, 14) = 64.18$, $MSE = 568$, $p < 0.001$.

Cross-dimension (as compared to intradimension) change costs are modulated by the type of search: The magnitude of cross-dimensional change costs critically depends on the type of search. In singleton conjunction search, cross-dimensional changes increased RTs substantially compared to non-changes, by 90 ms (841 vs. 751 ms), $t(14) = 5.1$, $p < 0.001$, two-sided; intradimension changes (as compared with non-changes) also increased RTs, $t(14) = 2.2$, $p < 0.05$, two-sided, although only by 22 ms (758 ms vs. 736 ms). The RT costs induced by cross-dimensional changes were significantly larger than those associated with intradimensional changes, $t(14) = 5.56$, $p < 0.001$, two-sided.

By contrast, in singleton *feature* search, cross-dimensional changes, but not intradimensonal changes, produced significant RT costs: cross-dimension (40 ms cost, 488 ms vs. 448 ms), $t(14) = 7.96$, $p < 0.001$, two-sided; intradimension (10 ms cost, 443 ms vs. 433 ms), $t(14) = 1.68$, $p = 0.12$, n.s. Again, RT costs were significantly larger with cross- than with intradimensional changes, $t(14) = 4.1392$, $p < 0.01$, two-tailed.

Finally, cross-dimensional change costs were significantly larger in singleton conjunction search as compared to singleton feature search, $t(14) = 2.379$, $p < 0.05$, two-sided; interaction dimension uncertainty $\times$ search type $\times$ change condition, $F(1, 14) = 5.66$, $MSE = 966$, $p < 0.05$.

The error (miss) rate effects tended to reinforce the RT effects: there were significant main effects for the factors search task, dimension uncertainty, and change condition; furthermore, the dimension uncertainty $\times$ change condition interaction and the target dimension $\times$ search type $\times$ change condition interaction were significant, search task: $F(1, 14) = 9.152$, $MSE = 0.00771$, $p < 0.01$; dimension uncertainty: $F(1, 14) = 7.686$, $MSE = 0.00584$, $p < 0.01$; change condition, $F(1, 14) = 9.331$, $MSE = 0.00481$, $p < 0.01$; dimension uncertainty $\times$ change condition, $F(1, 14) = 8.474$, $MSE = 0.003062$, $p < 0.05$; target dimension $\times$ search type $\times$ change condition, $F(1, 14) = 7.794$, $MSE = 0.00333$, $p < 0.05$.

Discussion

As expected, the type of search affected RTs: singleton feature search yielded faster performance than singleton conjunction search. In both types of task, RTs were significantly slower for cross-dimension search than for intradimension search; that is, uncertainty with respect to the target-defining dimension significantly increased RTs.

Color- and motion-defined targets were not detected equally efficiently as indicated by the main effect of target dimension. The significant interaction between search type and target dimension that was evident in the RT (but not the error) data indicates that this difference in search efficiency was unequal between the singleton conjunction and singleton feature search tasks: detection of a motion-defined (as compared to a color-defined) target was more strongly affected by the necessity to combine information from two visual dimensions.

Further analysis of the actual change trials revealed significant RT costs related to visual dimension changes: target detection was slowed in dimension change as compared to no-change trials. The extent to which target detection was affected by cross-trial changes of target features was dependent on dimension uncertainty (as indicated by the significant interaction between change condition and dimension uncertainty): overall, changes across visual dimensions, but not changes within a given dimension, resulted in prolonged RTs. In addition, the dimension change effects differed between the two types of task (as indicated by the significant interaction among change condition, dimension uncertainty, and search type): Cross-dimensional search costs were higher in singleton conjunction compared to singleton feature search. The error (miss) rate effects reinforced the RT effects.

Taken together, these results indicate that cross-dimensional search costs as observed in singleton feature search also manifest in more complex, singleton conjunction search tasks with the costs being actually

←

(gray) search. (d) Reaction times (dots) and error rates (bars) for color targets in the intradimension condition, separately for conjunction (black) and pop-out (gray) search. (e) Reaction times (dots) and error rates (bars) for motion targets in the cross-dimension conditions, separately for conjunction (black) and pop-out (gray) search. (f) Reaction times (dots) and error rates (bars) for motion targets in the intradimension condition, separately for conjunction (black) and pop-out (gray) search.

substantially increased compared to simple singleton feature search.

In singleton feature search, the cross-dimension search costs in a given change trial have been attributed to suboptimal dimensional weight settings established in the previous trial (Found & Müller, 1996; Müller et al., 1995; Müller et al., 2003). The same account can be extended to the cross-dimension change costs observed in singleton conjunction search: These costs, too, may originate from inappropriate prior weight settings, which are, however, additionally modulated by carry-over effects specifically related to conjunction search—in particular, settings specifying which conjunction of dimensions was relevant in the previous trial. If this extension holds, explicit and valid prior information specifying the relevant conjunction of features in the upcoming trial should reduce the cross-dimension search costs back to the level observed in singleton feature search. The effects of such semantic dimension precues were investigated in Experiment 2.

Experiment 2

As confirmed by Experiment 1, cross-dimensional change costs are increased in singleton conjunction relative to singleton feature search. These two types of visual search differ with regard to the amount of endogenous control required to detect the target. Whereas in singleton-feature search target detection is largely stimulus-driven, in conjunction search top-down endogenous control is, arguably, essential for detecting the target item (e.g., Weidner et al., 2002). Although detecting a singleton feature target requires little top-down control, target detection can be facilitated by appropriate endogenous settings. Such settings not only decrease the time required to detect the target overall, but also lessen the impact of dimension changes across trials (Müller et al., 2003; Weidner et al., 2009). Thus far, however, the effects of endogenous control on dimensional change costs have never been investigated for singleton conjunction search. Given this, Experiment 2 was designed to examine whether the increased dimensional change costs in singleton conjunction (relative to singleton feature) search can be attributed to inappropriate top-down settings carried over to the current from the previous trial. To this end, observers in Experiment 2 were presented with valid semantic precues at trial start, enabling them to establish an appropriate endogenous set for the secondary target dimension. This would then be expected to reduce any cross-dimensional change costs attributable to (on change trials) false top-down settings regarding the secondary dimension.

Methods

Participants

Sixteen observers with ages ranging from 20 to 29 (mean age 25) years participated in Experiment 2. They were all right-handed and had normal or corrected-to-normal vision.

Stimuli and task

The stimuli used in Experiment 2 were identical to those in the cross-dimension conjunction search condition of Experiment 1. Stimuli consisted of small and large, color, filled-in squares moving sinusoidally on either the horizontal axis or in a +45°- or −45°-oriented axis relative to the horizontal. The squares were colored either red, blue, or green. A potential target was defined by a conjunction of a constant primary dimension, namely, size: the target was always large with a secondary, across trials–variable dimension, which could be either color or motion direction. A target was either (large and) red or blue or, alternatively, (large and) oscillating diagonally on the +45° or −45° axis.

Procedure

Prior to the onset of the search display, a semantic cue was presented for 700 ms, indicating the secondary defining dimension of the upcoming target. The cue consisted of the German word for either "color," "motion," or "neutral." While "color" and "motion" cues specified the secondary target-defining dimension with a validity of 80%, "neutral" cues were non-predictive as to the definition of the upcoming target. Following cue offset, a blank screen was shown for 850 ms, which was followed by the presentation of the search display (Figure 3a). Presentation of the search display was terminated after 2500 ms or after the observer's response. Trials with "neutral" cues were presented in separate blocks (one third of the blocks) from trials with "color" or "motion" cues (randomized within blocks, two thirds of the blocks). Blocks consisted of 30 trials each with blocks separated by 5-s breaks; in total, 33 blocks were presented in randomized order ("neutral" blocks interspersed with "color"/"motion" blocks) so that each observer performed 990 trials altogether.

Results

Repeated-measures ANOVAs of RTs and error (miss) rates were performed with the factors cueing condition (valid vs. neutral vs. invalid cue) and target dimension (color vs. motion). Figure 3b and Table 3 present the mean correct target-present RTs and error

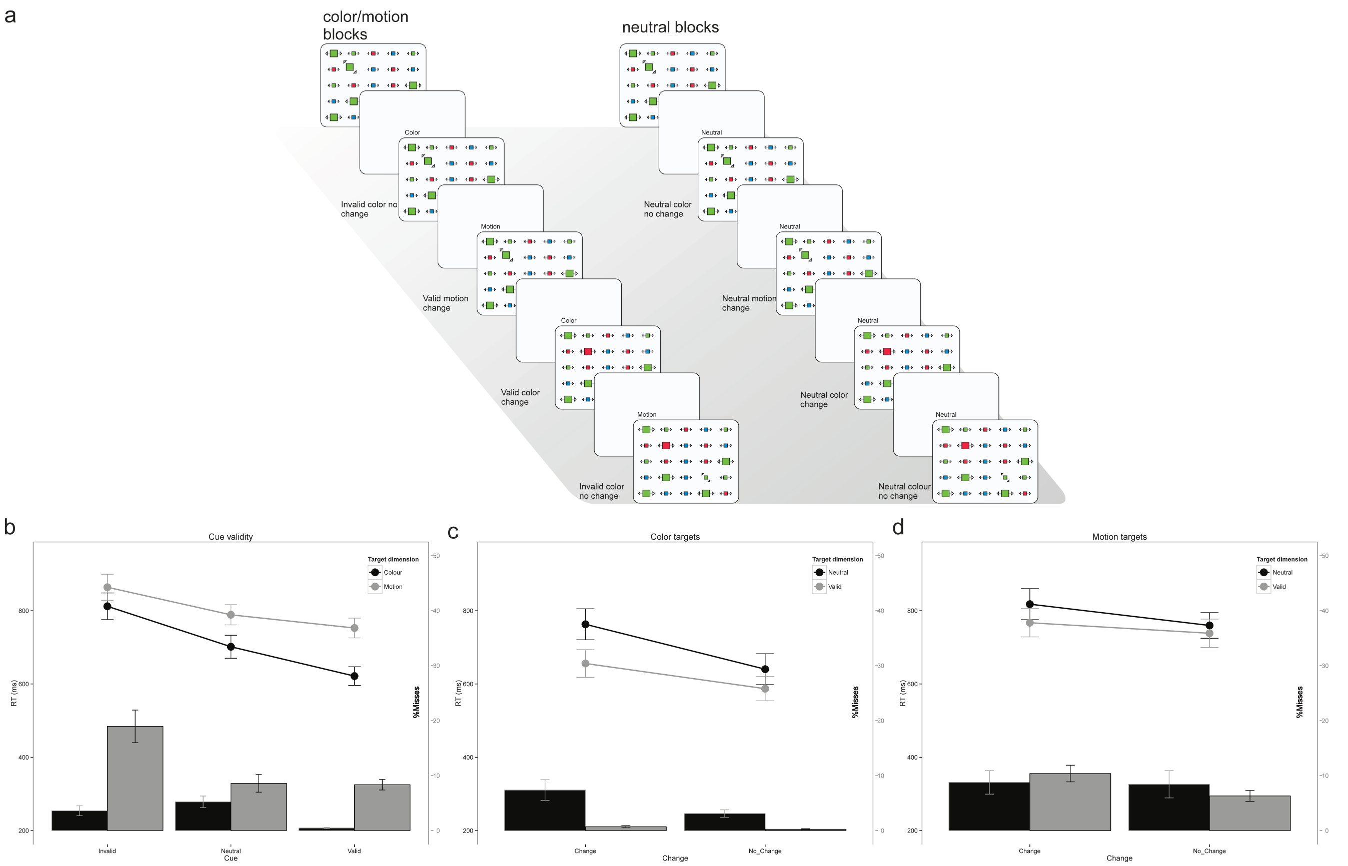

Figure 3. (a) Sequences of sample trials from the color/motion cueing condition (left) and the neutral cueing condition (right) of Experiment 2. (b) Reaction times (dots) and error rates (bars) for color (gray) and motion targets (black), separately for the different cueing conditions. (c) Reaction times (dots) and error rates (bars) for color targets for valid (black) and invalid (gray) cueing conditions, separately for change (left) and no-change trials (right). (d) Reaction times (dots) and error rates (bars) for motion targets for valid (black) and invalid (gray) cueing conditions, separately for change (left) and no-change trials (right).

rates for the different cueing conditions separately for the different secondary target-defining dimensions.

Overall RT and error effects

Cueing effects: Valid cueing decreased the search RTs compared to the neutral-cueing condition for both color- (622 ms vs. 702 ms) and motion-defined targets (753 ms vs. 789 ms). In contrast, invalid cueing increased the RTs for color- (812 ms vs. 702 ms) and motion-defined targets (864 ms vs. 789 ms).

Target dimension: As in Experiment 1, color-defined targets were detected faster than motion-defined targets (662 ms vs. 777 ms). Furthermore, cueing effects tended to be more marked overall for color-defined as compared to motion-defined targets although the interaction was not significant.

	Color		Motion		Sum	
	RT (ms)	% misses	RT (ms)	% misses	RT (ms)	% misses
Experiment 2						
Invalid	759	4	832	19	796	12
Neutral	640	5	760	9	700	7
Valid	587	0	738	8	663	4
x̄	662	5	777	12		

Table 3. Experiment 2: Mean RTs and miss rates for color and motion targets, separately for the different cueing conditions (valid, neutral, invalid).

	Change		No change		Sum	
	RTs (ms)	% misses	RTs (ms)	% misses	RTs (ms)	% misses
Experiment 2						
Valid mot.	767	10	738	6	753	8
Valid col.	656	1	587	0	622	0
x̄	711	5	663	3	687	4
Neutral mot.	818	9	760	8	789	9
Neutral col.	763	7	640	3	702	5
x̄	790	8	700	6	745	7
Overall	751	7	681	5		

Table 4. Experiment 2: Mean RTs and miss rates for color and motion targets, separately for the valid and neutral cue validity and the secondary-dimension change (change vs. no change) conditions.

The ANOVA of the error (miss) rates also revealed the two main effects (cueing condition, target dimension) to be significant (Table 5) as well as their interaction. Miss rates were more marked overall with motion-defined than with color-defined targets (12% vs. 5%). Invalid cues induced higher miss rates than neutral and, in particular, valid cues (12% vs. 7% vs. 4%). With motion-defined targets, invalid cues were particularly detrimental relative to neutral cues (19% vs. 9%), $t(15) = 2.89$, $p < 0.05$, two-tailed, and valid cues (19% vs. 8%), $t(15) = 3.74$, $p < 0.01$. In contrast, with color-defined targets, miss rates were comparable between invalid and neutral cues (4% vs. 5%), $t(15) = 1.04$, $p = 0.31$, n.s), and valid cues produced a reduction relative to neutral cues (0% vs. 5%), $t(15) = 4.1317$, $p < 0.001$, two-sided. Thus, overall, the miss rate effects reinforced the RT effects.

Cross-trial transition effects

In order to evaluate the effects of valid cueing on cross-trial changes of the secondary target-defining dimension, a second analysis was performed, comparing RTs and error rates between change and no-change trials with valid and, respectively, neutral cueing. (Trials following invalid cueing were not included in this analysis as the number of [available] change trials was too small to permit a reliable analysis [only 17 trials per observer].) The data were examined by a three-way ANOVA with the factors change condition (change vs. no change), (secondary) target dimension (color vs. motion), and cueing condition (valid vs. neutral); see Table 5 for details of the ANOVA results.

Figure 3c and d present the mean correct target-present RTs and miss rates for color-defined (3c) and, respectively, motion-defined targets (3d) separately for

	RT			Misses		
Variable	*Df*	*F* score	*p*	*Df*	*F* score	*p*
2-way ANOVAs*						
Cueing condition	1.15, 17.3	25.698	<0.001	1.8, 27.1	9.8305	<0.001
Target dimension	1, 15	20.414	<0.001	1, 15	24.724	<0.001
Cueing condition × target dimension	1.2, 17.9	2.293	0.14 n.s.	1.3, 18.8	7.4767	<0.01
3-way ANOVAs†						
Change condition	1, 15	47.468	<0.001	1, 15	11.15	<0.01
Cueing condition	1, 15	47.327	<0.001	1, 15	3.392	<0.1
Target dimension	1, 15	60.605	<0.001	1, 15	25.34	<0.001
Change condition × cueing condition	1, 15	14.65	<0.01	1, 15	0.001	0.976 n.s.
Change condition × target dimension	1, 15	8.677	<0.05	1, 15	0.014	0.907 n.s.
Cueing condition × target dimension	1, 15	5.986	<0.05	1, 15	8.399	<0.05
Change condition × target dimension × cueing condition	1, 15	0.555	0.468 n.s.	1, 15	6.086	<0.05

Table 5. ANOVA results for Experiment 2. *Notes*: * with the factors cueing condition (valid vs. neutral vs. invalid) and secondary target dimension (color vs. motion). † with the factors change condition (change vs. no change), secondary target dimension (color vs. motion), and cueing condition (valid vs. neutral).

secondary-dimension change and no-change trials as a function of cue validity (valid, neutral). For color-defined targets, valid, as compared to neutral, cueing not only decreased the search RTs (along with the miss rates) for both change (656 ms vs. 763 ms) and no-change trials (587 ms vs. 640 ms), it also decreased the RT costs associated with a change (vs. no-change) in the secondary target-defining dimension from 123 ms (neutral: 763 ms vs. 640 ms) to 69 ms (valid: 656 ms vs. 587 ms). The same pattern was evident with motion-defined targets: valid, compared to neutral, cueing decreased RTs (and error rates), for both change- (767 ms vs. 817 ms) and no-change trials (738 ms vs. 760 ms); also, it decreased the change RT costs from 58 ms (neutral) to 29 ms (valid).

Discussion

Valid cueing of the secondary target-defining dimension in singleton conjunction search decreased the time required to detect the target relative to neutral and invalid cueing conditions (as evidenced by the significant main effect of cueing condition in the two-way ANOVA; see Table 5). This effect was statistically equivalent for both color- and motion-defined targets (the cueing condition × target dimension interaction was not significant; see Table 5).

The RT costs associated with a change versus a no-change in the secondary target-defining dimension (as observed in Experiment 1) were also evident in Experiment 2 (as evidenced by the significant main effect of the factor change condition; see Table 5). Although change costs were observed for both dimensions, they were overall more marked for color-defined as compared to motion-defined targets (indicated by the significant change condition × target dimension interaction, consistent with Experiment 1).

Importantly, the change costs were altered significantly by the factor cueing condition: valid cueing decreased the change RT costs relative to neutral cueing (as indicated by a significant interaction between the factors cueing condition and change condition)—a pattern evident for both secondary target-defining dimensions. Prior knowledge of the secondary dimension defining the upcoming target can thus be used to lessen the effect of visual dimension changes, suggesting that a large portion of the increased change costs in singleton conjunction search (under effectively "neutral" cueing conditions) are due to the carryover across trials of (in change trials) false top-down settings. This finding furthermore illustrates that dimension-specific coding of visual information has its pendant in endogenous control. However, dimension change costs were not completely abolished by valid cueing: that is, change costs were still evident on valid-cue trials, planned t test, $t(15) = 4.8805$, $p < 0.005$, suggesting that endogenous control settings can only partly overcome stimulus-driven intertrial effects.

Experiment 3

Experiments 1 and 2 both indicate that cross-dimensional change costs, as first demonstrated for singleton feature search, also exist—and are, in fact, markedly increased—in singleton conjunction search. Furthermore, the findings in Experiment 2 indicate that the increased change costs arise on a level of processing that is susceptible to top-down control. A fundamental question concerns how top-down control accesses the different, target-defining visual dimensions in conjunction search and how the available processing resources are allocated to them. Experiment 3 was designed to investigate the effects of top-down control on the primary target-defining dimension and on initial filtering processes by exploiting "visual marking" (Watson & Humphreys, 1997). In visual-marking paradigms, the presentation of a preview display containing a subset of (task-irrelevant) distractors is meant to permit the active—space- and/or feature-based—inhibition of irrelevant items, thereby effectively reducing a conjunction search task to an "efficient" feature search task. Exactly how visual marking works is not crucial for the present purposes. According to Watson and Humphreys, marking is likely to involve both space-/object-based suppression (e.g., with static distractors) and the inhibition of whole feature maps (e.g., with moving distractors). Crucially, however, visual marking is likely to be an active, top-down operation as evidenced by findings that marking is compromised when observers have to perform a secondary, nonsearch task in parallel with the search task (Humphreys, Watson, & Joliceur, 2002; Olivers & Humphreys, 2002; Watson & Humphreys, 1997).

Applied to the present paradigm, if the preview display contains all small (nontarget) items observers would be able to suppress these prior to the presentation of the (task-relevant) large items, one of which is either differently colored or differently moving. Consequently, as search needs to operate only on a representation of the large items (the small ones are inhibited!), the task becomes effectively a singleton feature search. Visual marking of a primary target-defining dimension (in the present study: size) should thus replace the first filtering step in singleton conjunction search. Furthermore, marking permits selection of the primary target-defining dimension to be separated in time from that of the secondary dimension. As a result, processing resources bound to the primary dimension in standard conjunction search

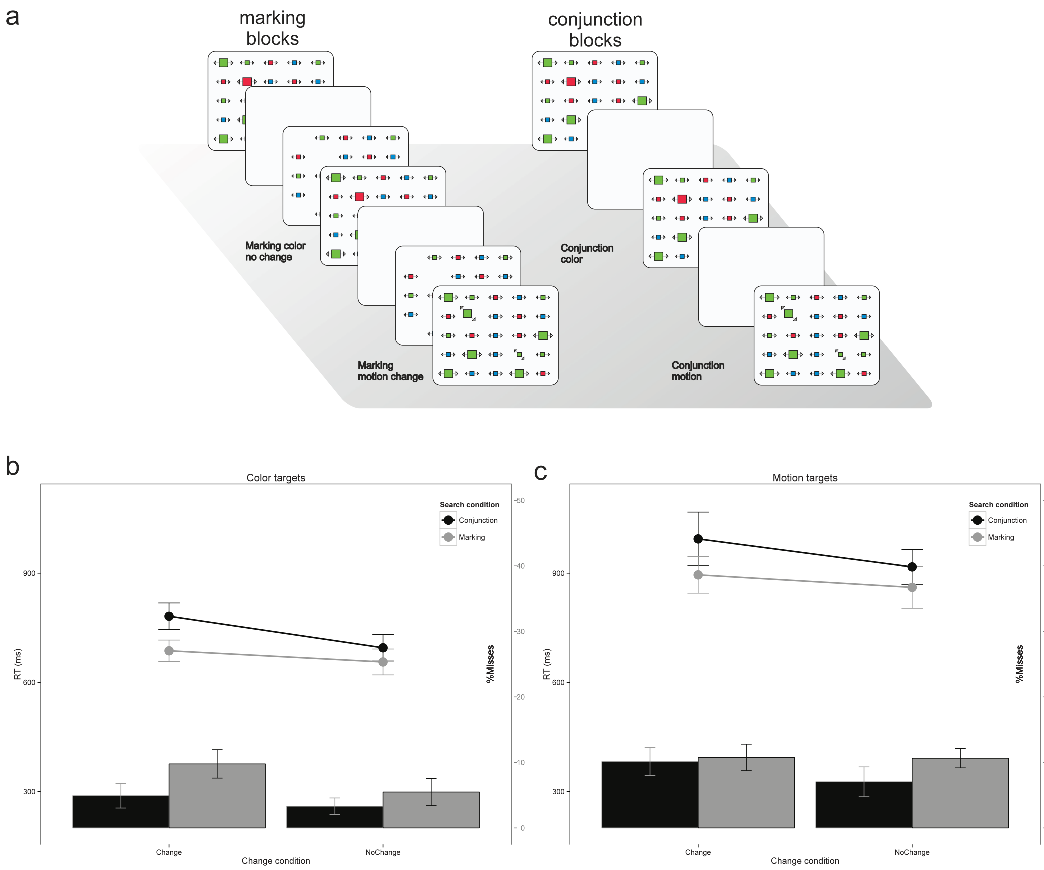

Figure 4. (a) Sequences of sample trials from the preview/visual-marking (left) and the standard conjunction search condition (right) of Experiment 3. (b) Reaction times (dots) and error rates (bars) for color targets in the conjunction (black) and preview/visual-marking search conditions (gray), separately for change (left) and no-change trials (right). (c) Reaction times (dots) and error rates (bars) for motion targets in the conjunction (black) and preview/visual-marking search conditions (gray), separately for change (left) and no-change trials (right).

would become available for processing the secondary target dimensions following visual marking. Accordingly, cross-dimensional change costs were expected to be reduced under conditions of visual marking.

Methods

Participants

Eighteen observers with ages ranging from 19 to 34 (mean age 28) years participated in Experiment 3. They were all right-handed and had normal or corrected-to-normal vision.

Stimuli and task

Observers performed a singleton conjunction search, which was basically identical to the conjunction search conditions in Experiments 1 and 2 (see Figure 4a). In order to investigate the effects of visual marking, a preview condition was added in which a subset of the distractors, namely all small items (recall that the target was never "small"), appeared on the screen prior to the presentation of the entire search display. The preview display was presented for 2 s, after which time the remaining (i.e., the large) items were added to the display. In order to match the standard conjunction search condition and the preview condition in terms of the temporal presentation parameters, in the former condition, an empty screen was shown for 2 s prior to the presentation of the search display. The search displays proper consisted of 25 items in both conditions. In line with the tasks in Experiments 1 and 2, observers had to detect (i.e., respond positively to) the presence of a large item that was either red or moved (oscillated) on a +45°-oriented axis relative to the horizontal or otherwise give a target-absent response.

Procedure

The two different search conditions, each consisting of 240 trials, were presented block-wise (blocks of 30 trials each, separated by 5-s breaks). (Five of the 18

	Change		No change		Sum	
	RTs (ms)	% misses	RTs (ms)	% misses	RTs (ms)	% misses
Experiment 3						
Conjunction mot.	994	10	917	7	956	9
Conjunction col.	781	5	695	3	738	4
x̄	888	8	806	5	847	6
Marking mot.	895	11	861	11	878	11
Marking col.	687	10	656	5	671	8
x̄	791	9	758	6	775	7
Overall	839	9	782	7		

Table 6. Experiment 3: Mean RTs and miss rates for color and motion targets, separately for standard conjunction and preview (visual-marking) search and for secondary-dimension change and no-change trials.

observers performed a shorter version of the experiment with only 162 trials per condition.) Condition order was counterbalanced across observers.

Results

Table 6 presents the mean correct target-present RTs and error (miss) rates for change and no-change trials in the two different search conditions (standard conjunction, preview), separately for color- and motion-defined targets. Repeated-measures ANOVAs of RTs and error (miss) rates were performed with the factors search condition (standard conjunction, preview), change condition (cross-trial change vs. no change), and secondary target dimension (color vs. motion); see Table 7 for details of the ANOVA results.

Search conditions

As can be seen from Table 6, search RTs were overall slower in standard conjunction search compared to the preview condition (847 ms vs. 775 ms; significant main effect of search condition). Cross-trial changes (vs. no changes) of the secondary target-defining dimension (from color to motion or vice versa) significantly slowed detection times (839 ms vs. 782 ms; significant main effect of change condition). Importantly, these change costs were markedly reduced in the preview condition (33 ms) relative to the standard conjunction search condition (82 ms) (significant change condition × search condition interaction) (Figure 4b and c). (Although performance was overall slower with motion versus color as the secondary target-defining dimension [significant main effect of target dimension], this effect pattern did not differ between the two secondary-dimension conditions.)

Planned t tests revealed RTs to be significantly prolonged for change relative to no-change trials in the preview condition, $t(17) = 1.98$, $p < 0.05$, one-tailed, as well as the conjunction condition, $t(17) = 5.2$, $p < 0.001$.

An analogous ANOVA of the error (miss) rates revealed a significant main effect of target dimension, a marginally significant effect of change condition, and a significant effect of search condition (see Table 7). Apart from the main effect of search condition, these effects reinforced the RT findings.

	RT			Misses		
Variable	*Df*	*F* score	*p*	*Df*	*F* score	*p*
Change condition	1, 17	25.24	<0.001	1, 17	4.435	<0.1
Search condition	1, 17	13.88	<0.01	1, 17	4.295	<0.1
Target dimension	1, 17	39.52	<0.001	1, 17	5.788	<0.05
Change condition × search condition	1, 17	4.672	<0.05	1, 17	0.004	0.952
Change condition × target dimension	1, 17	0.012	<0.914	1, 17	0.593	0.452
Search condition × target dimension	1, 17	0.227	0.64 n.s.	1, 17	0.3	0.591
Change condition × search condition × target dimension	1, 17	0.087	0.772 n.s.	1, 17	1.911	0.185

Table 7. ANOVA results for Experiment 3: Three-way ANOVAs with the factors change condition (change vs. no change), secondary target dimension (color vs. motion), and search condition (conjunction vs. marking).

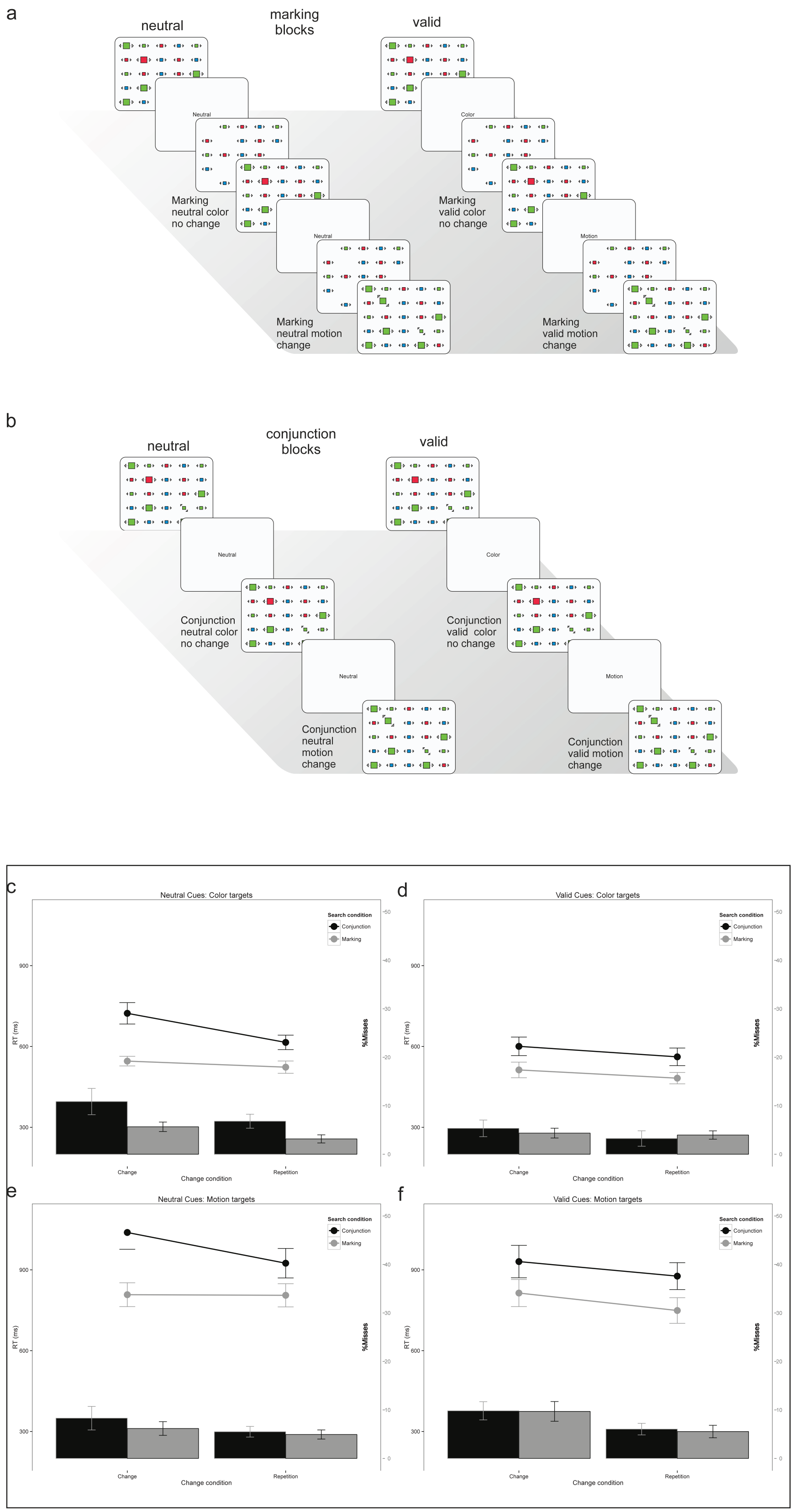

Figure 5. Sequences of sample trials from (a) the visual-marking and (b) the conjunction search condition of Experiment 4, separately for neutral (left) and valid (right) cueing. (c) Reaction times (dots) and error rates (bars) for color targets in the neutral cueing condition for conjunction (black) and preview/visual-marking search (gray), separately for change (left) and no-change trials (right). →

Discussion

Presentation of a preview display decreased the time required to detect the target, indicating that observers were able to make use of the preview display, marking the previewed distractors as irrelevant. (However, the preview condition was also associated with a marginally increased miss rate compared to standard conjunction search, suggesting a speed-accuracy trade-off contribution to the RT effect.)

Furthermore, cross-trial changes of the secondary target-defining dimension reliably increased target detection times in the preview as well as the standard conjunction search condition. Critically, however, presenting a preview display of irrelevant distractors prior to the target set of items significantly reduced the RT costs associated with changes of the secondary target dimension. The residual RT costs were of a similar magnitude to those observed in the singleton feature search condition of Experiment 1 (33 ms vs. 36 ms). This suggests that visual marking effectively turns singleton conjunction search to a singleton feature search, thus eliminating the cause for the enlarged change costs in singleton conjunction search.

Experiment 4

Taken together, Experiments 2 and 3 indicate that prior information about the primary and, respectively, secondary target-defining dimensions—that is, visual marking (of the small items) and semantic precueing (of the likely secondary target-defining dimension)—help reduce the RT costs associated with a cross-trial change in the secondary target-defining dimension. In principle, combining valid precueing and visual marking should permit observers to establish an optimal top-down set with optimized attentional weights for both the primary (minimal weight) and the precued secondary target-defining dimension (maximal weight). Assuming that observers are able to operate both top-down sets together, this would be expected to further reduce the costs associated with changes of the secondary dimension.

To examine this prediction, Experiment 4 independently varied top-down modulation of the primary and secondary target-defining dimensions by combining a preview (visual marking) procedure (as in Experiment 3) with semantic precueing (as in Experiment 2).

Methods

Participants

Sixteen observers with ages ranging from 21 to 27 (mean age 24.4) years participated in Experiment 4. They were all right-handed and had normal or corrected-to-normal vision.

Stimuli and task

The stimuli used in Experiment 4 were identical to those in Experiments 1, 2, and 3. Stimuli consisted of small and large colored squares oscillating (moving) sinusoidally on either the horizontal or a +45°- or −45°-oriented axis. The square colors were either red, blue, or green. A potential target was defined by a conjunction of a primary dimension (i.e., size): The target was always large, and a secondary dimension could be either motion direction. A target was either large and red or large and oscillating on a +45°-oriented axis.

Procedure

Four different kinds of experimental conditions were presented in separated blocks. Half of the blocks involved visual marking, that is, presentation of a preview display prior to the onset of the search display (Figure 5a); in the remaining blocks, the task required standard singleton conjunction search (Figure 5b).

The preview display consisted of a subset of the distractors: the small items, which were visible on the screen for 1000 ms prior to the presentation of the entire search display. The cue, in separate blocks, consisted of the German word for either "color" or "motion" (100% valid; block type 1) or, respectively, "neutral" (block type 2; 50% valid).

The remaining half of the blocks involved a standard conjunction search task (without preview display). In line with the visual-marking blocks, half of the blocks of the standard conjunction search task involved valid cueing, and half involved neutral cueing. Overall, 16 blocks, of 90 trials each, were presented to the observers in two different sessions.

←

(d) Reaction times (dots) and error rates (bars) for color targets in the valid cueing condition for conjunction (black) and preview/visual-marking search (gray), separately for change (left) and no-change trials (right). (e) Reaction times (dots) and error-rates (bars) for motion targets in the neutral cueing condition for conjunction (black) and preview/visual-marking search (gray), separately for change (left) and no-change trials (right). (f) Reaction times (dots) and error-rates (bars) for motion targets in the valid cueing condition for conjunction (black) and preview/visual-marking search (gray), separately for change (left) and no-change trials (right).

	Change		No change		Sum	
	RTs (ms)	% misses	RTs (ms)	% misses	RTs (ms)	% misses
Experiment 4						
Neutral						
Conjunction mot.	1039	8	925	6	982	7
Conjunction col.	723	11	615	7	669	9
$\bar{x}$	881	10	770	7	826	8
Marking mot.	808	6	806	5	807	6
Marking col.	546	6	523	3	535	5
$\bar{x}$	677	6	665	4	671	5
Overall neutral	779	8	717	5	748	7
Valid						
Conjunction mot.	931	10	877	6	904	8
Conjunction col.	601	5	562	3	582	4
$\bar{x}$	766	8	720	5	743	6
Marking mot.	814	10	749	6	782	8
Marking col.	513	4	482	4	498	4
$\bar{x}$	664	7	616	5	640	6
Overall valid	715	7	668	5	691	6
Overall	747	8	692	5		

Table 8. Experiment 4: Mean RTs and miss rates for color and motion targets, separately for neutral and valid cueing conditions and for secondary-dimension change and no-change trials as well as for the different search conditions (conjunction vs. marking).

Results

Table 8 presents the mean correct target-present RTs and error (miss) rates for change and no-change trials in the two different search (standard conjunction, preview) and cueing conditions (valid, neutral) separately for color- and motion-defined targets. Repeated-measures ANOVAs of RTs and error (miss) rates were performed with the factors search condition (standard conjunction, preview), cueing condition (valid, neutral), change condition (cross-trial change vs. no change), and target dimension (color vs. motion); see Table 9 for details of the ANOVA results.

Overall RT effects

The RT data replicate the findings of the previous experiments. Motion-defined targets were detected less efficiently overall than color-defined targets (868 ms vs. 571 ms; significant main effect of target dimension). More importantly, target detection times were slowed overall when the secondary target-defining dimension changed across trials compared to when it repeated by 55 ms on average (747 ms vs. 692 ms; significant main effect of change condition). Furthermore, presentation of preview displays shortened target detection times overall compared to standard conjunction search by 129 ms on average (655 vs. 784 ms; significant main effect of search condition). Finally, valid cues reduced target detection times overall compared to neutral cues by 57 ms combined across secondary target-defining dimensions (748 ms vs. 691 ms; significant main effect of cue validity).

The secondary-dimension change costs were significantly reduced by preview displays (search condition $\times$ change condition interaction). Furthermore, the preview effect was significantly reduced with valid as compared to neutral precues (search condition $\times$ cue validity interaction). Preview displays were more beneficial for motion-defined targets than for color-defined targets (preview benefits of 149 ms and 109 ms, respectively; significant search condition $\times$ target dimension interaction). Finally, the secondary-dimension change costs were modulated by the provision of preview displays and precues as to the secondary target-defining dimension (significant search condition $\times$ cue validity $\times$ change condition interaction).

For a more hypothesis-guided analysis of the effect pattern, a series of planned t tests (with p values Bonferroni-corrected for multiple comparisons) were performed, examining, first, the overall RT benefit deriving from the provision of (a) preview displays and (b) precues as to the target dimension and, second, the specific benefits deriving from these manipulations in terms of the reduction of the secondary-dimension change costs. Overall, compared to the standard

Variable	RT			Misses		
	Df	*F* score	*p*	*Df*	*F* score	*p*
Search condition	1, 15	25.51	<0.001	1, 15	3.031	0.102
Cue validity	1, 15	13.6	<0.01	1, 15	0.449	0.513
Change condition	1, 15	73.45	<0.001	1, 15	13.81	<0.001
Target dimension	1, 15	112.8	<0.001	1, 15	3.429	<0.01
Search condition × change condition	1, 15	11.45	<0.01	1, 15	3.046	0.101 n.s.
Search condition × cue validity	1, 15	8.974	<0.01	1, 15	5.389	<0.05
Search condition × target dimension	1, 15	12.98	<0.01	1, 15	0.924	0.352 n.s.
Cue validity × change condition	1, 15	0.898	0.358 n.s.	1, 15	0.001	0.976 n.s.
Cue validity × target dimension	1, 15	0.714	0.411 n.s.	1, 15	14.73	<0.01
Change condition × target dimension	1, 15	0.213	0.651 n.s.	1, 15	0.403	0.535 n.s.
Search condition × cue validity × change condition	1, 15	7.981	<0.05	1, 15	0.11	0.745
Search condition × cue validity × target dimension	1, 15	0.002	0.962 n.s.	1, 15	3.028	0.102
Search condition × change condition × target dimension	1, 15	0.015	0.906 n.s.	1, 15	0.249	0.625
Cue validity × change condition × target dimension	1, 15	1.366	0.261 n.s.	1, 15	1.69	0.213
Search condition × cue validity × change condition × target dimension	1, 15	0.776	0.392 n.s.	1, 15	0.351	0.563

Table 9. ANOVA results for Experiment 4: Four-way ANOVAs with the factors search condition (standard conjunction vs. visual marking), secondary-dimension cue validity (valid vs. neutral), secondary-dimension change condition (change vs. no change), and secondary target dimension (color vs. motion).

conjunction search condition (neutral cueing, no preview), valid cueing alone (no preview) produced an overall RT benefit of 83 ms (826 ms vs. 743 ms), planned t test: $t(15) = 3.66$, $p < 0.05$; preview displays alone (neutral cueing) produced a benefit of 155 ms (826 ms vs. 671 ms), $t(15) = 5.38$, $p < 0.001$; and preview displays combined with valid cueing produced a benefit of 186 ms (826 ms vs. 640 ms), $t(15) = 5.37$, $p < 0.001$. The differential benefits deriving from (a) valid cueing alone (83 ms), (b) preview alone (155 ms), and (c) preview combined with valid cueing (186 ms) differed significantly (or at least marginally) among each other, (a) versus (b): $t(15) = 2.98$, $p < 0.05$; (b) versus (c): $t(15) = 2.91$, $p = 0.0541$. This pattern suggests that provision of a preview alone is the main contributor to the benefit in target detection RTs (relative to standard conjunction search) whereas an additional precue specifying the secondary target dimension adds relatively little over and above this benefit.

RT cross-trial transition effects

The RT costs associated with changes in the secondary target-defining dimension were also modulated by the provision of small-item preview displays and secondary-dimension precues. In standard conjunction search (neutral cueing, no preview), secondary target-dimension changes relative to no changes increased RTs by 111 ms (881 ms vs. 770 ms), $t(15) = 5.3$, $p < 0.001$, two-tailed. Compared to this baseline of 111 ms, preview displays alone (neutral cueing) reduced the change cost to 12 ms (677 ms vs. 665 ms), $t(15) = 2.4$, $p = 0.29$, n.s., which corresponds to a 99-ms benefit relative to the baseline, $t(15) = 4.53$, $p < 0.01$. Valid cues alone (no preview) decreased the cost to 46 ms (766 ms vs. 720 ms), $t(15) = 2.9$, $p < 0.11$, n.s., which corresponds to a 65-ms benefit relative to the baseline, $t(15) = 2.17$, $p = 0.46$, n.s. And preview displays combined with valid cues reduced the cost to 48 ms (664 ms vs. 616 ms), $t(15) = 3.4$, $p < 0.05$, corrected, which corresponds to a 63-ms benefit relative to the baseline, $t(15) = 2.69$, $p < 0.16$, n.s. Although, unexpectedly, the benefit with preview displays alone (neutral cueing) was numerically larger than the benefits with valid cues alone (no preview) and combined preview displays plus valid cues (99 ms vs. 65 ms and 63 ms, respectively), the differences were, in fact, not significant, 99 ms versus 65 ms: $t(15) = 1.85$, $p = 0.83$; 99 ms versus 63 ms: $t(15) = 2.40$, $p = 0.29$; 65 ms vs. 63 ms: $t(15) = 0.05$, $p = 0.96$, n.s.

Error effects

Overall, miss rates tended to support the results from the RT analysis (Tables 8 and 9). Changes, as compared to repetitions, of the secondary target-defining dimension increased the rate of misses by 2.63% (7.53% vs. 4.90%), and motion-defined targets tended to be missed more often than color-defined targets (6.99% vs. 5.44%). Valid as compared to neutral cueing was more effective in reducing the miss rates when no preview was provided (reduction from 7.87% to 6.11%), compared to when a preview display was presented (reduction from 5.89% to 4.98%). Furthermore, cue validity had a differential effect on miss rates for targets defined with different secondary dimensions: valid as compared to invalid cues reduced the miss rates for color-defined targets (from 6.63% to 4.23%) but not for motion-defined targets (which actually showed a numerical cueing cost, rather than a benefit: 6.22% vs. 7.77%).

Discussion

As indicated by the significant main effects, observers were able to use both the preview displays and the (100% valid) semantic precues in order to enhance their search performance. The results obtained in Experiment 4 replicate the findings obtained in Experiments 2 and 3. Under standard conjunction search conditions (without preview; similar to Experiment 2), valid (vs. neutral) cueing of the secondary target-defining dimension reduced both the overall time taken to detect the target as well as the RT costs associated with a cross-trial change in the secondary target-defining dimension. Likewise, under neutral cueing conditions (similar to Experiment 3), provision of a preview (vs. no preview) of the small (nontarget) items reduced both the overall RTs and the RT costs associated with a change in the secondary dimension. Overall, the beneficial effects of preview provision were larger than those associated with valid precueing, both in terms of the overall RT benefits as well as the reduction of change costs.

However, although combining the presentation of a preview display with the provision of valid precues produced a significant overall RT benefit over and above that associated with the preview alone (186 ms vs. 155 ms), no further reduction of the change costs was observed. Rather, if anything, the change costs under combined (preview + precue) conditions were increased relative to the preview-alone condition. This might be owing to some overestimation of the benefit (in terms of change cost reduction) in the preview-alone condition (in which the change cost reduction was overall much larger compared to the equivalent conditions of Experiment 3: change cost with preview: 33 ms in Experiment 3 vs. 12 ms in Experiment 4; note that in Experiment 4, the change cost was practically zero for motion-defined targets) and, perhaps, an underestimation in the combined condition. In any case, it appears that observers are limited in their capability of implementing both top-down sets, namely visual marking of small items and weighting of the precued secondary target dimension, together.

It may well be that, due to limitations in executive control, observers implement only the "visual-marking" set (directed to the primary dimension) prior to the presentation of the preview display but defer implementing the "precueing" set (directed to the secondary dimension) until the presentation of the target set of items—in which case, the latter would come too late to further modulate (over and above the effect of marking) the processing of the target display on the current trial. To defer adjustment of the attentional weights for the secondary target-defining dimension to a later time would also make sense from an efficiency point of view: because visual marking (of items based on the primary dimension) yields greater benefits overall compared to setting oneself to the secondary dimension, it makes sense to implement the marking set with priority (and the dimensional set only later if at all). Finally, while late implementation of the precueing set might not help in the current trial, it might, in fact, be counterproductive on the subsequent trial because it might top-down reinforce the (for a subsequent change trial) inappropriate dimensional set, thus paradoxically increasing the change cost (cf. Olivers & Meeter, 2012).

In summary, for the dimensional weighting account, the implications would be as follows: (a) In standard singleton conjunction search, the primary dimension binds a large part of the available (limited) attentional weight; by releasing this weight, for instance, as a result of visual marking, this weight becomes available for processing the secondary dimensions. Because both dimensions would receive additional weight, processing becomes more efficient overall, and dimensional switch costs are reduced. (b) The extent to which further preknowledge of the secondary target-defining dimension can be exploited depends on the ability to implement top-down sets relating to the primary and secondary dimensions simultaneously. The present results would argue that this capability is limited, and observers proactively go for implementing that set that yields the greatest efficiency benefits, that is, the set relating to the primary dimension.

General discussion

Dimensional change costs are modulated in singleton conjunction search

The current data demonstrate that search for singleton conjunction targets is affected by the target-defining dimensions in previous trials. There are RT costs associated with changes of a (secondary) target-defining dimension, closely resembling the effects observed in singleton feature (pop-out) search (Found & Müller, 1996; Müller et al., 1995). However, compared to singleton feature search, uncertainty as to the secondary visual dimension defining a conjunctively defined singleton target yields greatly prolonged search RTs generally and markedly increased RT costs associated with a change in the secondary dimension specifically. Nevertheless, the striking similarity between the RT pattern observed in singleton feature and conjunction searches suggests that both effects are based on the same processes.

In principle, the increased change costs in singleton conjunction search may arise from increased demands on limited processing capacity compared to singleton feature search, or they may be caused by qualitatively different processes coming into play in conjunction search. In any case, different views of how singleton conjunction search is implemented in the system need not only coherently to account for the increased dimensional change costs observed in conjunction search, but also for the effects of symbolic precueing of the secondary target-defining dimension as well as of the preview of irrelevant nontarget items in the primary dimension. Experiments 2, 3, and 4 demonstrated that prior information with regard to the primary and secondary dimensions significantly expedited the overall search RTs as well as reducing the dimensional change costs.

A classic view states that singleton conjunction and singleton feature searches involve different processes (Treisman & Gelade, 1980): whereas pop-out search operates in parallel over the whole visual field, conjunction search involves spatially serial (in the extreme, item-based) processes. However, a number of exceptions have been reported since this distinction was initially proposed, which show that processing in conjunction search can be effectively restricted attentionally to a subset of items, reducing the overall number of items that need to be searched to locate the target (e.g., Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & Van der Heijden, 1995; Motter & Belky, 1998). Applied to the present task, when the target is defined by a conjunction of (large) size with either an odd-one-out color or an odd-one-out motion direction, search may be restricted to the large items among which the odd-one-out item would then pop out within its dimension, yielding (near) flat search RT/set size functions (in fact, Weidner and Müller [2009] found near-flat function for the present type of conjunction task with set size varying between 25 and 36 items and slope effects of 7.2 ms/item). Accordingly, compared to singleton feature search across variable (primary) dimensions, detection of a singleton conjunction target would require an additional, size-based filtering process, but following the filtering operation, the subsequent processing of the secondary visual dimension would operate in much the same way as in singleton feature search. The (additional) filtering process, however, would prolong search RTs overall.

Treisman (1988) argued that dimension change costs in singleton feature search are owing to the need to serially switch checking from one dimension—in which the target was defined in the previous trial (but which failed to yield a target signal in the current, change trial)—to the alternative dimension to determine whether (or not) this contains a target signal. This would be consistent with the above notion of sequential filtering processes. A more recent, and more elaborate, variant of this account is the Boolean-map theory of visual attention proposed by Huang and Pashler (2007). Huang and Pashler assume that an observer is able to consciously access only one feature value per dimension at a time. However, feature values from different dimensions can be combined by Boolean (map) operations; for example, the output from a selection process (based on one feature value) can subsequently be combined with that of another selection process (based on another feature value from a different dimension). In this view, selecting a conjunction target requires sequential, that is, (temporally) serial filtering processes generating separate (Boolean) maps and subsequent Boolean operations (e.g., logical and operation), combining the maps. For instance, detection of a target defined by size and color could be accomplished by a sequential filtering operation: filtering for size followed by filtering for color. If the target-defining dimensions (e.g., size plus color) repeat across trials, simply repeating the same set of filtering operations would make target detection efficient because the (size-color) target would be detected in this first cascade of filtering operations. In contrast, if the target-defining dimensions change across trials (e.g., trial 1: size plus color → trial 2: size plus motion), repeating the filtering operations from the previous trial (size → color) would fail to detect the target. Because a Boolean-map representation does not permit the featural properties of the represented objects to be differentiated (Huang & Pashler, 2007), a new cascade of altered filtering operations (size → motion) would become necessary to detect the changed target. Accordingly, the increased dimension change costs observed in singleton conjunction (as compared to singleton feature) search would be attributable to need (and associated time cost) to filter for size two times in order to discern the presence of the changed target.

Alternative views (e.g., Guided Search; Wolfe, 1994) emphasize parallel processing across both the visual field and different dimensions or features. Selection of conjunction targets is accomplished by integrating target signals computed in parallel across the visual field. These signals reflect local feature differences within different dimensions, which—according to Guided Search—can be top-down modulated by a (feature) selective bias, operating simultaneously in multiple dimensions, enhancing the precise features that define the (known) target. These signals are then integrated into an overall-saliency map, which provides the basis for focal-attentional stimulus selection. According to Wolfe, Butcher, Lee, and Hyle (2003), such feature-selective biases are still at work in singleton (feature and conjunction) searches, in which the precise target-defining features are not known, because the number of feature alternatives in each of, say, two critical dimensions is usually limited to, say, two, in which case there would only be four target alternatives (which does not exceed the limits of a search-biasing "template" system). Arguably however, this account would encounter a difficulty explaining why, with possible target-defining features kept constant (say, at two), the change costs are greater in cross-dimensional than in intradimensional search (i.e., when critical features change across separate dimensions vs. within the same dimension). To explain this, this account would have to incorporate some dimension-based limitation, for example, that it is harder to set up and/or keep available feature-biasing templates for separate dimensions. This would imply that if the first tested (template-biased) feature in the dimension carried over from the previous trial fails to yield a target signal, there would have to be a time-consuming switch to (or activation of) the alternative feature template in the other dimension (see, e.g., Krummenacher, Grubert, & Müller, 2010). However, while this would explain why switching would be harder across, compared to within, dimensions, it would fail to explain why cross-dimension change costs are larger in singleton conjunction, compared to singleton feature, search. To explain this, one would have to make additional assumptions along the lines of Treisman (1988) and Huang and Pashler (2007), according to whom the additional dimension change costs in singleton conjunction search are attributable to the need to repeat the size (template) based filtering process once the first testing process failed to yield a target signal. Thus, arguably, a model successfully explaining both greater change costs in cross-dimensional as compared to intradimensional search and larger costs in cross-dimensional singleton conjunction relative to singleton feature search requires (a) a dimensional organization of feature representations and (b) an overall limit of the capacity available for processing these dimensions.

A variant of a Guided-Search–type model assumes that singleton selection is modulated not by (multiple) feature-specific biases, but rather by a single biasing or "weighting" mechanism that operates on dimension-based feature contrast signals computed in parallel in multiple visual dimensions. The (proportion of the total) weight allocated to a dimension determines the influence of any feature contrast signals in this dimension on the integration stage: the larger the weight, the faster a signal in the respective dimension emerges on the overall-saliency map (Found & Müller, 1996; Müller et al., 1995). On this DWA, the cross-trial dimension change costs in singleton feature search and the enlarged costs in singleton conjunction search result from a single limitation in the total weight available to be shared among different dimensions. In singleton conjunction search, a target is defined in multiple visual dimensions: in the present paradigm, one fixed primary dimension and one of two variable secondary dimensions. Assuming that the (need to filter within the) primary dimension binds weight, less weight would be available for any of the secondary dimensions. As a result, it would take longer for target evidence to accumulate in the secondary dimensions, increasing the secondary-dimension change costs relative to singleton feature search.

Thus, according to the sequential-filtering accounts discussed above (Huang & Pashler, 2007; Treisman, 1988; Wolfe et al., 2003), enlarged secondary-dimension change costs in singleton conjunction, compared to singleton feature, search would arise due to a need to repeat the (size-based) initial filtering process once a carried over filter setting for the secondary dimensions fails to return a "hit" in order to check for a target signal in the alternative secondary dimension. By contrast, the parallel DWA assumes that, on a secondary-dimension change trial, a suboptimal (carried over) distribution of attentional weight results in a slower accumulation of information within the secondary target-defining dimension, slowing RTs for change trials. Given that the primary target-defining dimension continually binds weight, less weight would be available overall for the secondary dimensions, thus exacerbating the secondary-dimension change costs compared to singleton feature search.

Top-down effects on dimensional change costs: Semantic cues

In principle, both types of account predict a reduction of change costs once prior knowledge about upcoming target-defining dimensions is provided. Given that top-down control is able to set filtering rules a priori, a valid cue should prevent a wrong second filtering process and thus eliminate the need to rerun initial (size-based) filtering (in case the secondary dimension checked first does not contain a target). This would, however, imply that valid cueing should abolish dimensional change costs completely.

In contrast, the DWA allows for a gradual decrease of dimensional change costs, along with a gradual top-down guided redistribution from one secondary target-defining dimension to another. The results of Experiment 2 indicate that preknowledge of the secondary target-defining dimension can top-down reduce dimensional change costs quite significantly. They further show that although top-down control can, in principle, help prepare the system for the upcoming target-defining dimension, residual dimension change costs are still present. This may be taken as evidence in favor of parallel weighting accounts. (Note though that sequential filtering accounts might explain this finding by assuming that participants sometimes fail to change the top-down set in response to the precue.)

Top-down effects on dimensional change costs: Visual marking

More fundamentally, however, the two types of accounts differ with regard to the predicted secondary-dimension change costs when the initial and subsequent filtering steps can be temporally disentangled, such as in "visual-marking" paradigms, in which conjunction search is rendered more efficient by presenting a subset of nontarget items prior to the onset of the set containing the target (e.g., Watson & Humphreys, 1997).

A strict serial-filtering model would predict that RTs would be facilitated overall by the preview because visual marking does effectively do away with the need for the initial size-based filtering step. However, with a change in the secondary target-defining dimension in the current (relative to the preceding) trial, the initial size-based filtering would have to be carried out anew. This is because once a combined Boolean map (Huang & Pashler, 2007) has been generated, featural dissociations within this map are no longer possible (e.g., color and size maps cannot be dissociated from a combined representation) and because the "temporal separation" signals between the preview and the target display would have effectively decayed, thus making a size-based filtering operation necessary. In other words, the actual source of the enlarged secondary-dimension change costs would still be fully present as a result of which the secondary-dimension change costs should hardly be diminished compared to the standard conjunction search.

In contrast, the DWA would predict the opposite pattern. Visual marking (of the previewed, small items) would free the weight otherwise bound by the primary (size) dimension, thus effectively making more attentional weight available for the parallel (but likely unequally weighted) processing of the secondary target-defining dimensions, thereby decreasing the dimensional change costs. Experiment 3 clearly demonstrated that secondary-dimension change costs are greatly reduced by visual marking, providing evidence in favor of a parallel dimension-weighting account of cross-dimensional singleton conjunction search.

Top-down distribution of attentional resources across different visual dimensions

Experiments 2 and 3 strongly suggest that cross-dimensional search for singleton conjunction targets involves parallel weighting processes and that increased secondary-dimension change costs originate from capacity limitations in the processing weight that can be allocated to multiple relevant dimensions. Because attentional weight is bound by the primary target-defining dimension, less weight is left for the secondary dimensions, slowing search RTs overall as well as increasing the secondary-dimension change costs. In the two experiments, semantic precueing of the secondary target-defining dimension, color or motion, or, respectively, visual marking of the small-sized items greatly reduced the change costs with the marking effect being larger than the cueing effect. Experiment 4 replicated these findings in a single (within-participant) experiment and showed further that a combination of precueing with marking reduced the overall search RTs even further (compared to marking alone) albeit not in an additive manner; also, the combination had no further effect on the secondary-dimension change costs (compared to that of marking alone), likely owing to a central-executive limitation in setting up and coordinating the two types of top-down visual sets necessary for visual marking and cue-based processes. Overall, however, the findings strongly suggest that the enhanced (secondary) dimension change costs in singleton conjunction search originate from a limited amount of attentional weight available to be allocated to the different, task-relevant dimensions. Because the (need to process a) primary target-defining dimension binds attentional weight, parallel accumulation of target information within the second dimension is accordingly delayed, resulting in enhanced RT costs. This view of parallel coding of target signals in multiple dimensions in singleton conjunction search concurs with recent findings reported by Weidner and Müller (2009). Weidner and Müller observed that RTs to redundantly defined singleton conjunction targets, that is, targets defined in two secondary (color plus motion) dimensions, violated Miller's (1982) race model inequality, demonstrating parallel-coactive processing of two secondary target dimensions.

Summary and conclusion

The present study investigated the allocation of dimension-based processing resources in singleton conjunction search. Cross-trial changes, as compared to repetitions, of a secondary target-defining dimension induced a pattern of RT costs similar to that observed

for changes of the primary dimension in singleton feature search, however, with the change costs being substantially increased. Top-down control mechanisms are able to reduce these increased change costs. Both valid semantic precues as to the secondary target-defining dimension as well as preview displays allowing for visual marking of an irrelevant subset of items within the primary dimension significantly reduced the secondary-dimension change costs. The cueing effects illustrate that the increased change costs are due to the carryover across trials of, in change trials, inappropriate dimensional top-down settings; they furthermore suggest that processing resources are distributed in parallel (though not necessarily equally) across multiple target-defining dimensions. The effects related to visual marking indicate that inhibition of search-irrelevant items within the primary target-defining dimension frees attentional weight otherwise bound to this dimension, allowing for more efficient parallel processing within the secondary target-defining dimensions. Finally, limitations in central-executive control processes that manage top-down settings related to the primary and secondary target-defining dimensions are likely to prevent settings in response to the preview displays and dimensional precues to be optimally coordinated. Taken together, the present results indicate that increased RT costs as observed in cross-dimensional singleton conjunction search, compared to singleton feature search, originate in a parallel and top-down controlled distribution of attentional processing resources across all target-defining dimensions.

Keywords: selective attention, conjunction search, dimension weighting

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