Explaining efficient search for conjunctions of motion and form:

Evidence from negative color effects

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Abstract

Dent et al., (2011) showed substantial costs to search when a moving target shared color with a group of ignored static distractors. The current study further explored the conditions under which such costs to performance occur. Experiment 1 tested whether the negative color sharing effect was specific to cases where search showed a highly serial pattern. The results showed that the negative color sharing effect persisted in the case of a target defined as a conjunction of movement and form even when search was highly efficient. Experiment 2 examined the ease with which participants could find an odd colored target amongst a moving group. Participants searched for a moving target amongst moving and stationary distractors. In Experiment 2A participants performed a highly serial search through a group of similarly shaped moving letters. Performance was much slower when the target shared color with a set of ignored static distractors. The exact same displays were used as in Experiment 2B, however participants now responded present for targets that shared the color of the static distractors. The same targets that were previously difficult to find were now found efficiently. The results are interpreted in a flexible framework for attentional control. Targets linked with irrelevant distractors by color tend to be ignored. However this cost can be overridden by top-down control settings.

Human behaviour takes place in a complex, cluttered, dynamic environment. The human visual system can not simultaneously process all of this information (e.g. see Broadbent 1958; Tsotos, 1990). Mechanisms of selection are required in order to prioritise relevant and to deprioritise irrelevant stimuli for further processing and action. The visual search task (see Chan & Hayward, 2013; Wolfe 1998; Wolfe & Horowitz, 2004; for reviews) in which an observer is required to find a target amongst a set of spatially distributed distractors, has been used extensively to characterise these mechanisms of selection. In the visual search task the slope of the function relating the number of potential targets to RT (search slope) is the primary measure of the efficiency of a given search. Certain targets may be detected highly efficiently with little increase of RT as the number of items increases. In the extreme when the search slope is close to zero, all the items in a display may be processed in parallel. For example, the visual system is highly sensitive to differences in the gross features of objects, a single red item amongst green items may “pop-out” effortlessly from a display, and may be very difficult to ignore (e.g. Theeuwes, 1992; see Theeuwes 2010 for a review). According to Treisman’s Feature Integration Theory (FIT; Treisman & Gelade, 1980; Treisman, 2006) and its derivatives (e.g. Guided Search, Wolfe, 1994; 2007; Dimension Weighting, Müller, Heller, & Ziegler, 1995; Krummenacher & Müller, 2012) these basic features are represented in distinct feature maps within dimensional modules that code the gross distribution of a particular feature in the environment, thus these feature maps alone may signal the presence of unique features. In contrast, recovering more detailed information, including how multiple features are conjoined, requires spatial selection, producing search slopes greater than 0, as single items or small groups of items are inspected in turn.

Revisions to this basic FIT architecture allow the feature maps to guide selection even for complex conjunctively defined targets; like a red X amongst green Xs and red Os (e.g. Treisman & Sato, 1990; Wolfe, 1994; Wolfe Cave & Franzel, 1989). Instead of spatial selective attention being deployed at random, selection may be guided towards locations that contain relevant features and away from locations that contain irrelevant features. According to the Guided Search model (GS, Wolfe et al., 1989; see also Wolfe, 1994; 2007) feature maps activate locations in an activation map, the level of which determines the likelihood that an item will be selected. By increasing the weighting on inputs from target feature maps, search can be biased towards likely target locations, increasing the speed of search. In some cases where the target is defined as a conjunction of two highly discriminable features (e.g. a red X amongst green Xs and red Os, Wolfe et al., 1989; moving X amongst static Xs and moving Os, McLeod, Driver, & Crisp, 1988) parallel search may result, where there is little or no cost as more items are added to the display. A similar architecture was also suggested by Treisman & Sato (1990), however they proposed inhibition of locations containing non-target features rather than activation of locations containing target features. Other authors while accepting the basic architecture of FIT emphasise the role of different feature dimensions (e.g color vs. orientation) rather than specific feature values (e.g. red vs. horizontal) as targets for attentional modulation (e.g. Müller, Heller, & Zeigler 1995; Krummenacher & Müller 2012). Thus, according to the Dimension Weighting model (DW) feature contrasts within different feature dimensions may be differentially weighted, according to top-down goals. Appropriate weights across multiple dimensions can lead to efficient conjunction search (see Weidner & Müller, 2009; Weidner, Pollmann, Müller, & von Cramon, 2002).

Exactly how the different features of objects compete and cooperate to guide selection is not fully understood. One important issue regards the independence of guidance by multiple features. According to FIT and related models it is possible to independently control guidance by distinct features, since there is no direct mechanism for interactions between distinct feature maps from different dimensions (aside from common projections to a master activation map). More recent explicit computational models of how of feature maps drive activity in a master activation or saliency map also make the assumption that there is independent summation across dimensions (e.g. Itti & Koch, 2000). This independence of guidance by the multiple features of objects is an important point of contrast between FIT and the Attentional Engagement Theory (AET) proposed by Duncan & Humphreys (1989; 1992). According to AET stimuli gain or lose attentional weight to the extent that they match a target template held in working memory. Importantly, the attentional weights of different stimuli that share features are not independent but linked, so that items that are grouped together tend to gain or lose weight together. Importantly, this “weight linkage” exists even if the linkage is on the basis of a feature that is not explicitly relevant.

The specific notion of weight linkage is clearly related to the subsequent broader articulation of the integrated competition hypothesis (ICH e.g. Duncan, Humphreys, & Ward, 1997). ICH states that objects compete for representation in multiple brain systems coding specific features, but that this competition is integrated such that as objects gain or lose dominance in one system their representation in other systems follows suit. ICH gains support from behavioural studies demonstrating that it is easier to encode two properties of one object than two properties of two objects (e.g. Duncan, 1984, see Scholl, 2001 for a review). More recent neuroimaging experiments also support the notion of integrated competition at the level of multiple properties of single objects. O’Craven, Downing and Kanwisher (1999) measured brain responses to superimposed images of faces and houses one of which could be in motion. The results showed that even though all three attributes occupied the same location, attention to movement also led to an enhanced response in the category specific area representing the moving object (face or house).

Specifically in the context of visual search over multiple items, there are several demonstrations of failures of independent feature based control of search guidance in the literature. Found (1998) (see also, Takeda, Phillips and Kumada 2006) showed that task irrelevant size differences that correlated with task relevant color and form differences improved search performance, consistent with non-independence.

Braithwaite and colleagues (e.g. Braithwaite, Humphreys, & Hodsoll, 2003; Braithwaite, Humphreys, Hulleman, & Watson, 2007; Andrews, Watson, Humphreys, & Braithwaite, 2011) have investigated the issue of independence of guidance extensively in the context of temporal selection. When the cue for selection is temporal (one set of stimuli appears 1 second before the remaining distractors and the target), the early appearing distractors can be effectively excluded from search (see Watson, Humphreys, & Olivers, 2003). However this preview benefit, is associated with costs under some conditions, e.g. targets that share color with the early appearing distractors are difficult to find, consistent with non-independence of selection by temporal and color cues. Braithwaite et al., (2003) explain this negative color carry-over effect in terms of inhibition of the color of the distractors contingent on active inhibitory processes applied to the locations of the early appearing distractors, in the time-window prior to the appearance of the target.

Recently, Dent et al. (2011) extended this phenomena of negative color carry-over to a non-temporal selection cue; segmentation by motion. Participants searched for a moving target letter amongst static and moving distractors. When the target shared color with the static distractors it was very difficult to find. This negative color effect occurred despite clear evidence that participants could use movement to restrict search to a moving group. The results of Dent et al. (2011) challenge the proposal of FIT, GS and DW that search may be guided by motion independently of color, but are consistent with the proposal of ICH and AET that the attentional weights of items that share features change together (weight linkage). Thus one interpretation of the results reported by Dent et al. (2011) is that when the target shares the color of the static distractors it inherits a loss of attentional weight or priority due to weight linkage with the rejected static distractors, making it difficult to find.

Search efficiency and the independence of guidance cues

However, one issue for the study of Dent et al., (2011) is that search through the moving heterogeneous letters was difficult showing an extremely serial letter-by-letter pattern of performance (search slope in the baseline condition was around 80ms per item). Half the letters moved and half were stationary, so guidance of search by *motion* was possible. However, the target letter Z or N could not be distinguished from the distractors (HIVX) by a single form feature, but only the spatial configuration of its parts, rendering guidance by *form* inert. It is possible that the non-independence of control exhibited by participants in this study is specific to a situation where selection through a subset is driven by a systematic serial search.

Models in the guided search family were initially developed to account for cases of highly efficient conjunction search (e.g. conjunctions of color and form, form and motion etc.). In these situations a single location in the master activation map will have substantially higher activation than other locations (on target present trials) and will be selected with one of the very first deployments of spatial attention. Although this first deployment of spatial attention may be made on the basis of computations that treat multiple features independently, subsequent shifts of attention may not. In the task of Dent et al. (2011) shifts of attention through the moving group will not be effectively guided by an activation map, since all potential moving targets will have similar activation values. When spatial attention shifts through a target group without strong guidance to any particular location from the activation map, the system is likely to fall back on other principles to direct search. One such heuristic could be deliberate strategic avoidance of items sharing color with static distractors. Initial selection of a static distractor may also automatically and involuntarily lead to priming of same colored distractors, leading to a disadvantage for targets colored differently. Thus, in this regard the study of Dent et al., (2011) whilst providing an important demonstration of non-independence, does not rule out that independence as predicted by GS may be observed so long as GS mechanisms are effectively operating to drive *efficient* search.

Segmentation and second-order parallel processing

Models like GS which attempt to explain search and selection using a map that sums signals across different feature dimensions, may be contrasted with other models which use segmentation and grouping processes to select targets. For example, McLeod, Driver, & Crisp (1988) introduced the idea of a motion filter, in order to explain their finding of efficient search for targets defined by conjunction of movement and shape (e.g. a moving X amongst moving Os and static Xs). The motion filter is a dedicated functional motion processing system, realised by neural hardware in the brain (e.g. hMT/V5+). The motion filter preferentially represents moving items, and is sensitive to their gross form. Essentially the motion filter allows form-processing operations to be restricted to a moving group of objects, allowing detection of an odd shaped item amongst a moving group. Although, some of the predictions made by the motion filter account have been disconfirmed (e.g. von Mühlenen, & Müller, 2000; 2001), Ellison, Lane, & Schenk (2007) recently reinvigorated this hypothesis by demonstrating using TMS that even when of similar efficiency, search guided by motion rather than color recruited parietal regions to a smaller extent, depending primarily on intact sensory hMT/V5.

The general idea that the parallel computation of differences along a secondary dimension may be restricted to a subset of elements sharing features along a different primary dimension is referred to as second order parallel processing (e.g. Friedman-Hill and Wolfe, 1995). In addition to the idea of a motion filter, the idea of second order parallel processing forms an important component of some general models of search and selection (e.g. Grossberg, Mingola, & Ross, 1994; Huang & Pashler, 2007), where segmentation is not restricted to movement, but can operate for many other dimensions. Friedman-Hill & Wolfe (1995) experimentally explored the possibility of second-order parallel processing of orientation driven by color, by asking participants to search for a conjunctive target of known color but unknown orientation. Importantly, there was no single orientation or set of orientations that would always characterise the target; the target orientation on one trial could be the target colored distractor orientation on another. Here the logic was that if orientation was unknown search could not be *guided* towards a specific orientation. If form processing can be restricted to items in the target color, a target of unknown but unique orientation should pop-out nonetheless. Friedman-Hill & Wolfe concluded that whilst such color-driven second-order processing was possible it was time consuming to implement, thus second-order parallel processing may be of secondary importance compared to feature based guidance, at least when it comes to explaining efficient conjunction search.

More recent studies in the DW framework have further examined second-order parallel processing. Weidner and colleagues (Weidner et al., 2002; Weidner & Müller 2009; 2013) have explored second order processing of color and motion driven by primary segmentation by size. Participants searched for a large target, ignoring a set of small distractors heterogeneous in color and motion direction. The large non-targets were homogeneous and had fixed values of color and motion direction. Under these conditions so long as participants knew the target defining dimension (color or motion), there was no cost to performance from uncertainty regarding the specific color (red or blue) or motion (+45 or -45 degrees) value. In contrast substantial costs to performance arise when there is uncertainty regarding the dimension within which the target will be defined. In contrast to Friedman-Hill and Wolfe (1995) it appears that there are some stimulus configurations for which dimension based guidance is more important than guidance to a specific feature. Thus according to DW second order parallel processing can be achieved by feature-based filtering along a primary dimension coupled with high dimensional weight assigned to the secondary target defining dimension. When it is not possible to weight the secondary dimension optimally costs arise since the contribution of the appropriate dimension to saliency computations will not always be maximised.

Weidner and Müller (2009; 2013) argue that rather than a sequence of operations e.g. segmentation by size, then by motion or form as supposed certain models (e.g. Grossberg et al., 1994; Huang & Pashler, 2007) all the dimensions feed information into an activation map in parallel as in GS. Support for this assertion comes from the finding that a temporal preview of the small distractors (e.g. Watson & Humphreys, 1997) can greatly reduce the cost associated with not knowing the target dimension. If the cost for dimensional uncertainty arises since participants must check through both secondary dimensions on some trials then these costs should continue to be present under these preview conditions (Weidner & Müller, 2013). Additionally, when a target is dimensionally uncertain but happens to be defined redundantly on both dimensions performance is facilitated in a way consistent with coactivation from both secondary dimensions (Weidner & Müller, 2009). These results are consistent with limitations on the amount of dimensional weight that may be assigned. The majority of dimensional weight is assigned to the primary dimension, the remaining weight is assigned to the secondary dimensions. Large costs occur as a result of dimensional uncertainty since under these conditions the limited remaining dimensional weight cannot be reliably directed to the target defining dimension. The important point for the current work is that if participants can increase the weight assigned to the form dimension to reliably detect targets then they may be able to operate in a color-independent fashion.

Clearly in the study of Dent et al. (2011) second-order parallel processing would be ineffective as the target shared form features with the moving distractors. If second order parallel processing of form driven by motion is possible, or even obligatory as suggested by the idea of a motion filter, then when such second-order form processing is possible irrelevant color differences may then be immaterial. Likewise when participants are able to assign high dimensional weight to the target defining form dimension they may be immune to the effects of motion. Alternatively, once participants begin to search for an odd shaped item amongst the moving group, they may also become sensitive to odd colored items, essentially operating in a singleton detection mode (e.g. Bacon & Egeth, 1994) in the moving items. Dent et al. (2011) argued that their results were difficult to account for by a motion filter or other second order parallel processing accounts. However, the nature of the search task used in the Dent et al. (2011) study is not really an optimal test of the motion filter and related second-order parallel accounts. Thus it may be that the weight linkage of color and motion was observed in the study of Dent et al. (2011) not because search was serial per-se, but because second-order cues were absent.

The current study

In summary, it is certainly not clear that motion segmentation when it is used to drive a serial search through a relevant subset (as in Dent et al., 2011) operates according to the same mechanisms as when motion segmentation is used to efficiently detect form singleton amongst a relevant subset (as in McLeod et al., 1988). In efficient conjunction search, the target location is more clearly specified in the activation map. When participants rely to a greater extent on these guiding representations,movement may be treated independently of color. One aim of the present study then was to examine if the negative effect of sharing color with a set of static distractors would generalise to situations where search is more efficient. In cases of efficient search the where the contribution of a guiding activation map is maximised principles of independence may in fact hold. The current study tested this view by examining negative color effects in the case of efficiently detected movement-form conjunction targets. If participants continue to show negative color effects, even when the target is highly discriminable in form amongst the moving group, and participants have every incentive to either use an activation map, or second-order parallel processing, the importance of weight-linkage as general principle in search will be ratified. Furthermore fundamental problems with representing conjunctions of color and form (e.g. see McLeod et al. 1988), were ruled out by showing that targets that shared color with static distractors could be relatively efficiently detected when color was explicitly relevant.

Experiment 1

In Experiment 1 participants searched for a target letter (H or I) amongst distractor letters (see Figure 1). In the critical motion segmentation case, the target was presented amongst moving O and static H and I distractors. Thus the target always possessed different features from the other moving items but shared form features with the static items, the target was only distinguished from the distractors by a conjunction of movement and form. Although the exact form of the target (H or I) was unpredictable the horizontal and vertical features common to the targets were never present elsewhere amongst the moving distractors, thus guidance based on form feature maps will be possible. Importantly, the moving and static distractors were always colored differently. On half the trials the target shared color with the static distractors and was thus differently colored to the other moving items constituting a color singleton within the moving group. On the other half the target was the same color as the other moving items and different in color to the static distractors. Will the negative color carry-over effect generalise to this situation where a feature unique target is sought amongst a motion defined subset? The motion segmentation condition was contrasted with a half-set condition in which only the moving items were presented, in order to demonstrate that when the moving subset is presented in isolation performance is efficient.

In the experiment of Dent et al., (2011) the moving and static distractors consistently appeared in the same color throughout the experiment. For one group the static distractors were red and the moving distractors green and for one group this mapping was reversed. In the current experiments in order to rule out the possibility that any negative color effects are driven by the consistent pairing of a particular color with the static distractors, a set of 6 possible colors that were mapped onto the moving and stationary distractors at random were employed.

Method

Participants

Twelve students (4 males, 1 left handed) from the University of Essex, aged between 19 and 28 years (M=22.6), took part for course credit.

Equipment

Stimuli were generated by a Macintosh PowerPC Dual G5 computer, using routines programmed with the Psychophysics Toolbox extensions to MatLab (Brainard, 1997), and presented on a Mitsubishi 23sb 17-in screen.

Stimuli

The search displays were composed from the uppercase letters H I and O (see Figure 1 for illustration). Viewing distance was approximately 40 cm. The letters measured 0.6 x 0.6 cm (0.86° x 0.86°) and were composed of lines 0.6 x 0.6 cm (0.086°) wide. The H was composed of one horizontal line and two vertical lines, and the I two vertical lines and one horizontal line. The H and I were 90° rotations of each other, the O was a closed circle. The letters were positioned randomly within the cells of an 11 x 11 grid of 121 cells (excluding the center cell, which contained the fixation cross). The stimuli were bounded by an outline frame 0.3mm (0.043°) wide measuring 16 x 16 cm (22.6° x 22.6°), and the display center was marked by a fixation cross, 0.6 × 0.6 cm (0.86° × 0.86°), with each component line 0.3 mm (0.043°) wide. Static letters appeared centered within a cell, and moving letters were initially offset to the end point of the path they would move through. Motion took the form of a linear up/down oscillation (2.6 cm/s, 3.72 deg/s) centered on the relevant cell (magnitude of oscillation, 0.36 cm, 0.56°). Initial motion direction (up or down), was random across trials.

Design & Procedure

The design consisted of three factors: condition (motion segmentation, half-set) x target color (target color singleton, target color non-singleton) x number of moving letters (6, 12). The critical condition was the motion segmentation condition (see Figure 1 for illustration). Here either 12 or 24 letters were presented; half of the letters were static and the other half of the letters including the target moved (6 or 12). The static distractors were uniformly colored Hs and Is (presented in equal numbers), the moving distractors were uniformly colored Os of a different color to the static distractors. Target color was manipulated so that on half of the trials, the target was a color singleton in the moving group (sharing its color with the static items; target singleton case). On the remaining trials the target was the same color as the moving items, differing in color from the static group (target color non-singleton case). A single baseline condition was also included, in the half-set baseline condition, only the moving items from the motion-segmentation condition were presented; thus, displays contained only 6 or 12 moving items. On half of the trials, the target was a color singleton, and on the other trials, it was identical in color to the moving distractors (color singleton and non-singleton trials respectively). In both conditions a single moving target was always present and the task was to identify the target form (H or I), by pressing the Z or N key on the keyboard. Six colors (red, green, blue, yellow, cyan, pink) were possible; formed from all possible combinations of the values of 255 or 0 on the red, green, and blue channels of the monitor (excluding black and white). Which two colors would be present was determined at random with the constraint that no two colors were permitted to repeat on successive trials. Thus it was never the case that a target on trial n would take on the color of the static distractors on trial n-1.

The different conditions were presented to participants in separate blocks of trials, within which the other factors varied. Participants first completed one block of 24 practice trials for each of the two conditions, data from these practice blocks was discarded. Participants then completed two further blocks of each of the conditions (120 trials the first two blocks prefaced by 24 practice trials and the second two blocks prefaced by 8 practice trials). There were thus 60 trials for each cell of the experimental design. The two conditions alternated, with the order of presentation of counterbalanced over participants (ABAB or BABA).

Each trial commenced with a key-press from the participant. Each trial started with a blank screen for 100 ms, followed by the outline square and fixation cross for 500 ms. The search stimuli then appeared and began to move immediately. The display was cleared when the participant responded, and the next trial began.

Results

Accuracy: Accuracy was overall extremely high (98% correct, see Table 1 for breakdown) and too high to permit meaningful analysis.

RT: Incorrect trials (2.3%) and trials with RT <100ms or >10s (0.04%) were excluded. RT can be seen illustrated in Figure 2. Firstly, ANOVA with the factors of target color (singleton or non-singleton), condition (motion segmentation or half-set), and number of moving items (6 or 12) was conducted. Of critical importance the interaction between all three factors was significant $F(1,11)=21.72$, $p<0.001$, consistent with negative effects of the target sharing color with the static distractors on search slopes, in the motion segmentation condition.

In order to further explore the three-way interaction we separately analysed performance in each condition using ANOVA with 2 factors, target color and number of moving items. In the motion segmentation condition performance was overall slower ($F(1,11)=8.04$, $p<0.005$, for the main effect of target color), and less efficient on target color singleton trials (30 vs. 14.5 ms/item; $F(1,11)=21.95$, $p<0.001$ for the interaction between set size and condition, for the color singleton and non-singleton targets respectively). In contrast in the half-set condition performance was neither faster ($F(1,11)<1$, for the condition main effect) nor more efficient ($F(1,11)=1.22$, $p=0.292$ for the interaction between set-size and condition) as a function of target color. The highly efficient performance was indistinguishable for the color singleton and non-singleton cases (search slopes of 0.7 and 1.5 ms/item), although there was a significant main effect of number of moving items F(1,11)=9.75, p<0.01.

In the motion segmentation condition for color non-singleton trials whilst performance was relatively efficient in the group as a whole (14.5 ms/item) it was not as efficient as many conjunction searches (5-10 ms/item) that Wolfe (1998) designates as "quite efficient". However there was substantial variation in efficiency, Figure 3 shows the scatterplot of the relationship between conjunction search efficiency in the motion segmentation condition for non-singleton targets and the cost in efficiency resulting from the target sharing color with the static distractors (motion segmentation color singleton – non-singleton efficiency). It is clear to see that *every* participant shows some numerical cost in the color singleton case, although there is a significant correlation, this is driven by a single inefficient participant. In order to ensure that the negative carry over effect did not disproportionately reflect the performance of the least efficient participants the data from the motion segmentation condition were median split and the 6 most efficient participants were examined separately, here mean efficiency was 9.4 ms/item (see Figure 2 for illustration). The interaction between number of moving items and color in the motion segmentation condition continued to be present for these highly efficient participants F(1,5)=70.444, p<0.0001.

Discussion

Experiment 1 showed that even when the target is defined as a conjunction of movement and form there is a cost when the target shares color with the static items. Importantly, this cost occurred when participants were tuned to detect a salient featural difference amongst the moving group. Thus the negative color effect is not limited to situations where the target is similar in form to the other moving items. Furthermore, performance of the group was relatively efficient and response times were fast (around 1 second) compared to the previous report of Dent et al. (2011). Additionally, all participants, including those participants who exhibited highly efficient performance showed the color effect. Thus the effect is not a characteristic of a search mode in which selection operates in a serial item by item fashion.

In terms of general theoretical principles of search and selection, these results demonstrate a scenario where selection by motion and color are not independent. Thus GS and related models will require modification to incorporate this correlation between guidance from different features. The integration between different features in the control of search is a core principle of the ICH framework, and elements of this framework will need to be incorporated into any comprehensive account of search. But exactly how in detail should this negative color effect reported here be explained? AET as a more specific version of the general ICH framework provides a natural explanation in terms of weight-linkage and spreading suppression, but should the data be explained in terms of weight-linkage between the target and the moving items or weight-linkage between the target and the static items?

It is tempting to try to explain the effect by appeal to processes operating on the moving items. This explanation might appeal to improved target selection when it can be linked by color to the other moving items. However, it is important to note that interactions exclusively within the moving group cannot explain the data, if that were the case then we should also observe a cost when only the moving item are presented in the half-set condition. Clearly, at least the presence of a group of static distractors is necessary for the effect to occur. Still, one might contend that the contribution of the static items is to abolish any advantage associated with a first-order color singleton, and that over and above this, the cost should be explained in terms of interactions between the moving items. Firstly, although weight linkage between the target and moving distractors might help to distribute increased weight to the target based on motion, since the target is always moving and will receive increased weight directly, it is difficult to see how such sharing could further increase the weight. Secondly, such an explanation is untenable since it misses the point that the moving items are distractors, and these distractors are efficiently *rejected* from search, as shown by the relatively efficient performance here. In contrast to the experiment of Dent et al. (2011) where form was not a reliable guidance cue, in the current experiment participants were much more efficient at rejecting the moving distractors as evidenced by the search efficiency (14 ms/item, for non-singleton targets in the motion segmentation condition of the current experiment vs. 35 ms/item in Dent et al., 2011). Essentially, the target will have a stronger attentional weight than the moving distractors. Linking the target with these distractors by common color would make it *more* difficult to individuate the target, undermining the benefit from form guidance, leading to a *cost*, rather than the *benefit* which is in fact observed. Thus the most likely explanation is that when observers act rapidly to ignore a set of static distractors, which happen to have a particular color, by default other items that share color with these items tend to also get ignored. According to AET this is due to the attentional weight of the target being reduced due to weight linkage with the static distractors resulting in spreading suppression.

The difficulty to find a target that shares color with a group of static distractors, even though it is color unique amongst the moving group, and even when individuals are set to detect salient featural differences amongst that group is somewhat paradoxical. As outlined above one hypothesis here recruits the idea of second order parallel processing of the moving subset. According to this notion feature processing is constrained to apply separately to the moving group. Thus if participants are searching for a form unique item, it might be expected that since the locations of the target and the color singleton are perfectly correlated, an *advantage* would occur when the target was defined redundantly by a color difference, rather than the *cost* which is observed. There are at least two accounts of why second order color singletons fail to aid performance. One possibility is that these second order signals are difficult or impossible to generate as a result of the visual feature processing architecture (e.g. the idea that motion and form are paradigmatic examples of separable features). Indeed in the motion filter hypothesis of McLeod et al. (1988) the motion filter is “color blind”. Thus it is possible that weight linkage occurs, and redundancy gains are absent only when dynamic signals combine with color. A second possibility is that although it is in principle possible to generate such signals if color is explicitly task relevant, they are not generated automatically, and by default weight linkage is dominant.

More recent studies conducted within the framework of DW have contrasted the relative impact of uncertainty regarding the specific secondary feature or dimension defining the target. Weidner and Müller (2013; 2009, see also Weidner et al., 2002) demonstrated that when participants knew the primary basis for selection (e.g. size) the cost of uncertainty regarding the secondary target dimension (color or motion) was greater than the cost of uncertainty regarding the target feature (red or green). These dimensional costs could be partially overridden by a semantic precue consistent with the idea that participants can alter the weights assigned to differences originating in a particular dimension top-down, leading to enhanced performance. However, whether efficient detection of second order color targets is possible with the current stimuli, where movement is the primary segmentation cue is unknown. In order to test whether in principle second order color singleton targets can be detected efficiently if explicitly required we conducted Experiment 2.

Experiment 2

In Experiment 2 participants viewed displays similar to those used by Dent et al., (2011) but with random assignment of color to the different distractor types. In Experiment 2A participants searched for a Z or N target amongst moving and stationary HIVX distractors. In Experiment 2B participants searched exactly the same displays but this time were asked to detect the presence of an oddly colored item in the moving group. These specific stimuli were used in order to eliminate guidance by form, in order to isolate processing of color – motion conjunctions. Will color singletons in the moving group remain difficult to detect even when they are explicitly relevant?

Method

Participants

A total of 24 students from the University of Essex took part in return for course credit. In Experiment 2A there were 12 participants (3 males, 1 left handed) aged between 19 and 29 years (M=21). In Experiment 2B there were 12 participants (5 males, 3 left handed), aged between 19 and 31 years (M=20.8).

Equipment

As for Experiment 1.

Stimuli

The stimuli were displays of letters as in Experiment 1. However the specific letters used were different. All but one of the letters were selected from the letters, H, I, V, X, one, the target, was either Z or N (see Figure 4).

Design & Procedure

The design of Experiment 2A consisted of three factors: condition (motion segmentation, full-set, half-set) x target color (target singleton, target non-singleton) x display size in the reference motion segmentation condition (12, 24). The two baseline conditions (full-set and half-set) were constructed with reference to the critical motion segmentation condition. In the motion segmentation condition (illustrated in Figure 4) there were either 12 or 24 items, with half static and half moving (6 or 12 items). As for the motion segmentation condition in Experiment 1 the static items shared a uniform color selected from 1 of 6 possibilities. The moving distractors were assigned a different uniform color from one of the remaining possibilities. Target color was varied as for Experiment 1 with 50% of targets sharing color with the static letters (target color singleton) and 50% of targets sharing color with the other moving items (target color non-singleton). The full-set baseline condition was as for the motion segmentation condition, apart from here all the items moved. Thus in the full-set condition the target color manipulation was merely that targets that would have been color singletons in the motion segmentation condition appeared in a slight color majority (7 s. 5 or 13 vs. 11). The half-set condition was as for the motion segmentation condition except that here the static items were not presented (and thus true set-size was 6 or 12 items). In Experiment 2A the task was to identify the target form (Z or N) by pressing Z or N on the keyboard.

Participants completed each of the three conditions in a separate block of 144 trials (the first 24 trials were treated as practice and discarded). The order of presentation of the three blocks was counterbalanced over participants, such that each condition appeared equally often in each serial position. There were thus 30 trials per cell of the design. In addition participants completed a short block of 24 practice trials of each of the conditions (in the same order as the experimental blocks), prior to beginning the main experiment.

Experiment 2B was based on Experiment 2A with two major modifications: 1) Here the task was to simply detect if a target color singleton was present or not. 2) Since this task was not possible in the full-set condition when all items move (since here there is no true color singleton amongst the moving group) only the motion segmentation condition and the half-set baseline conditions were included. Participants pressed “Z” to indicate present and “N” to indicate absent. In Experiment 2B participants completed two blocks of experimental trials per condition, as for Experiment 1. There were thus 60 trials per cell of the design. In addition participants also completed one short block of 24 trials in each condition prior to commencing the experiment proper.

Experiment 2A Results

Accuracy: Accuracy was overall extremely high 98% correct (see Table 2 for breakdown) too high to permit meaningful analysis.

RT: Incorrect trials (1.97%) and trials with RT <100ms or >10s (0.53%) were excluded. RT can be seen illustrated in Figure 5. Of critical importance the three way interaction between all factors was significant $F(2,22)= 10.21$, $p<0.001$. In order to further understand the pattern of results in the three-way interaction, separate analyses were carried out comparing the motion segmentation condition against both the full-set and half-set conditions.

Motion Segmentation vs. Full-Set

ANOVA with the factors of target color (singleton non-singleton) condition (full-set, half-set, motion-segmentation) and set size in the motion segmentation condition (12, or 24 items), revealed a significant three-way interaction F(1,11)= 7.87, $p<0.05$, consistent with large costs on search efficiency for target color singleton trials only in the motion segmentation condition. The three-way interaction was further decomposed by means of separate analyses of each condition and separate analyses of color singleton and color non-singleton targets.

Considering the full-set condition there was no main effect of target color F(1,11)<1 nor any difference in efficiency F(1,11)=1.22, p=.294 as a function of target color. In contrast in the motion segmentation condition the slope was much higher (78 vs. 50 ms/item, F(1,11)=7.53, $p<0.05$, for the condition x set size interaction) when the target shared color with the static distractors in the color singleton case compared to the non-singleton case

For target color non-singleton trials, performance was faster (F(1,11)=50.89, $p<0.0001$, for the condition main effect) and more efficient (87 vs. 50 ms/item, F(1,11)=8.5, $p<0.05$ for the set size x condition interaction) in the motion segmentation compared to the full-set condition. In contrast when the target was a color singleton in the moving group, sharing color with the static distractors (when present), performance was faster (F(1,11)=5.64, $p<0.05$ for the condition main effect); but no more efficient (73 vs 78 ms item, F(1,11)<1 for the set-size x condition interaction), in the motion segmentation compared to the full-set condition. Importantly, the benefit obtained from motion segmentation (in terms of efficiency) is completely eliminated, when the target shares color with the static distractors.

Motion segmentation vs. Half-Set

ANOVA with the factors of target color (singleton non-singleton) condition (full-set, half-set, motion-segmentation) and number of moving items (6, or 12 items), showed a significant three-way interaction F(1,11)= 26.5, p<0.05. The three-way interaction was decomposed by conducting separate analyses for each target color; singleton and non-singleton, and for each condition.

In contrast to impaired performance in the color singleton case documented above for the motion segmentation condition, in the half-set baseline performance was actually more efficient if the target was a color singleton (F(1,11)=21.27, p<0.001, for the interaction between the number of moving items and target color, 35 vs. 9 ms/item). In the half-set condition, the effect of the number of moving items is significant for color non-singleton trials F(1,11)=48.79, p<0.0001, but only just if there is a color singleton F(1,11)=5.88, p<0.05.

Separate analysis of the color non-singleton trials showed that when the target was a color non-singleton performance was slower in the motion segmentation condition (F(1,11)=12.9, p<0.005, for the condition main effect); but the increase in RT as a function of the number of moving items did not differ between conditions (F(1,11)=2.33, p=0.155 for the interaction between the number of moving items and condition). Thus in the color non-singleton case motion segmentation is highly effective, with performance in the motion segmentation condition as efficient as when the static items are not present. When the target was a color singleton in the moving group performance was slower (F(1,11)=64.09, p<0.0001 for the condition main effect) and showed a larger increase in RT as a function of the number of moving items (F(1,11)=50.82, p<0.0001, for the number of moving items x display size interaction, 78 vs. 9 ms/item), in the motion segmentation compared to the half-set condition. Thus in the color singleton case motion segmentation is now ineffective, with performance much poorer when the static items are present (motion segmentation) compared to when they are absent (half-set).

Experiment 2B Results

Accuracy: Overall accuracy was high 96%, see table 3 for a breakdown. Error rates were 5% or less in all conditions except when there were 12 moving items in the motion segmentation condition, where 10% of targets were missed. Given the overall high accuracy further ANOVA was not conducted.

RT: Incorrect trials (4.2%) and trials with RT <100ms or >10s (0.14%) were excluded. RT can be seen illustrated in Figure 6. ANOVA with the factors of target color (singleton, non-singleton) condition (half-set, motion-segmentation) and number of moving items (6 or 12). Critically, the three-way interaction between all factors was significant, F(1,11)=13.37, $p<0.005$. In order to further understand the three-way interaction we conducted separate analyses of each condition. In the half-set condition although performance was slightly faster in the target present case, F(1,11)=8.75, $p<0.05$, there was no effect of set size F(1,11)=2.09, p=0.176, and no trace of an interaction between the two F<1. In the motion-segmentation condition performance was overall faster F(1,11)=14.17, $p<0.005$, and more efficient on color singleton trials (30 vs. 15 ms/item, F(1,11)=15.4, $p<0.005$, for the interaction between number of moving items and condition). Importantly, participants detected oddly colored items amongst a moving group relatively efficiently, and approximately as efficiently as participants found form unique targets in a moving group in Experiment 1.

Discussion

In Experiment 2 participants viewed displays similar to those used by Dent et al., (2011) (but with random assignments of colors to targets and distractors). In Experiment 2A when search was explicitly based on shape performance was generally less efficient than in Experiment 1 since the target is now defined by the spatial configuration of the constituent lines rather than any one simple form feature. Despite this difference the qualitative pattern of results was very similar; moving targets that shared color with the static distractors were extremely difficult to find, resulting in performance equivalent to when there was no segmentation cue present. In contrast when participants viewed *exactly the same displays* but with the task now to respond “present” to a color singleton the task was vastly easier with RTs reduced by about 1200 ms at the higher set size. Strikingly, participants were able to detect the presence of a color singleton amongst the moving group at least as efficiently as they responded to the form singleton of Experiment 1. It should be acknowledged that the relatively efficient RT performance in Experiment 2B did come at the cost of a small increase in miss errors as display size increased (6%). However, even if we take a conservative approach and correct the RT values according to Townsend and Ashby’s (1983) suggestion (RT/Accuracy), then the resulting search slope remains a respectable 20 ms/item, and remains more efficient than the 30 ms/item slopes seen for a color singleton target in Experiment 1. Thus it is not the case that there is a general problem in processing conjunctions of movement and color, conjunctions of color and motion and form and motion appear to be processed with similar levels of efficiency. However in order for these displays to yield efficient performance color differences must be an explicit part of the task set or target template.

Treisman and Sato (1990) also concluded that conjunctions of movement and form were not special and conjunctions of color and form could also be detected relatively efficiently. However, in these earlier studies all the distractors moved, but in different directions, since all items would be thus represented in a motion filter it is difficult to properly assess this hypothesis, in the current experiment the contrast was between moving and static items. Additionally in the study of Treisman and Sato (1990) participants knew in advance the specific color value that would characterise the target, in the current experiment specific target color was unknown. In the current experiment (see also Friedman-Hill & Wolfe 1995) there was no color or set of colors that could reliably differentiate the target from the distractors over the experiment, the target color on one trial could become the color of the moving distractors on another. The current experiment thus goes beyond a demonstration of relatively efficient search for color x motion conjunctions, it shows that color x motion conjunctions can be detected relatively efficiently even when there cannot be feature based guidance on the basis of color. Thus second order processing of color driven by motion is possible and can be achieved relatively efficiently.

General Discussion

Three experiments explored the conditions under which items that are color unique in a motion defined subset, but share color with a group of static distractors, result in efficient search performance. Experiment 1 showed that if observers are set to search for a target defined by a conjunction of motion and shape they may do so relatively efficiently. Even though search is relatively efficient and participants are set to detect feature differences in the moving group, color singletons in the moving group do not aid performance. In fact performance is *worse* not better when the target is both form and color unique. Experiment 2 explored if the failure of color unique targets to speed search was linked to a fundamental problem with second order color processing within a moving group. The results showed that targets that were exceedingly difficult to detect when color was not an explicit part of the task set, became easy to detect when color differences defined the target.

Similar negative color carry-over effects have been demonstrated in the context of preview search, when an early appearing set of distractors are rejected from search (e.g. see Braithwaite, Humphreys, & Hodsoll, 2003). Whether similar effects occur for segmentation based on all dimensions (e.g. color, depth, orientation, etc), or whether it is specific to segmentation driven by dynamic features remains to be fully explored. However, Andrews, Watson, Humphreys, & Braithwaite, (2011) explored negative color carry-over effects in preview search when both the old and the new items were moving. Here both the old and the new items are dynamic and so being dynamic or not does not reliably distinguish the old and new items. Under these dynamic conditions negative color-carry over effects were larger that when all items were static, suggesting that a simple dynamic vs. static distinction is not critical.

The results of Experiments 1 and 2A are easily accommodated within the broad framework of integrated competition (e.g. Duncan, Humphreys, & Ward, 1997; see also Duncan 1995). More specifically, the results may be explained by recruiting the idea of weight linkage discussed by Duncan & Humphreys (1989); when the target shares color with the static distractors the attentional weight of the target is linked to the low attentional weight of the static known to be irrelevant distractors and the target is suppressed. An explanation in terms of suppression gains independent support from other studies. Firstly, Driver, McLeod and Dienes (1992) showed that manipulating the heterogeneity of the motion trajectories of a set of distractors that did not share the target motion direction was more disruptive than a similar manipulation of those distractors sharing target motion direction. The authors interpret this finding in terms of disrupted inhibition of distractors with non-target motion as a consequence of increased heterogeneity. That disruption is greater for distractors without target motion than with target motion, suggests that inhibition of these distractors is primary. Secondly, Dent, Allen, Braithwaite, and Humphreys (2012) using a probe dot detection paradigm demonstrated costs for probes appearing on static distractors consistent with suppression of static distractors in motion – form conjunction search. Thus far from being a peculiarity of a certain kind of difficult search task, where the target is similar in form to other task relevant moving items, weight linkage seems to be a far more pervasive phenomenon. That weight linkage occurs even for rapid and efficient conjunction search, a situation for which GS and second-order parallel accounts were specifically developed provides special difficulty for these accounts.

Nor is it the case that combinations of color and motion pose special problems for the visual system. When explicitly task relevant in Experiment 2B, targets defined as odd colors in the moving group could be detected relatively efficiently. Indeed, odd colors were detected faster and more efficiently than targets that shared color with the static items in Experiment 1. Differences on multiple dimensions can not therefore be extracted simultaneously and combined automatically in this task, else redundancy gains (similar to those observed by Weidner & Müller, 2009) would be observed in Experiment 1, but they are not. Recent studies in the framework of DW demonstrate the importance of trial history in conjunction search (e.g. Weidner & Müller, 2009; 2013). Thus when the target defining dimension changes there is a cost relative to when it repeats. The explanation given by DW for this finding is that once the target is detected, high dimensional weight is applied to the dimension that defined it, when the dimension subsequently changes the weight settings are sub-optimal and there is a cost. The current experiments place clear limits on this reconfiguration of dimension weights consequent on target detection. The dimensional weight assigned to color when it is task irrelevant but happens to define the target does not increase. Had the weight increased in this way a benefit rather than a cost would be seen for singleton targets. Thus the reconfiguration of dimension weights consequent on target detection proposed by DW must be limited by explicit task relevance, changing only for dimensions marked as relevant. It appears that weight linkage for color and motion is dominant, and the visual system tends to make the assumption, that elements that share features with ignored distractors are unlikely to be targets. However, there is sufficient flexibility that these links can be broken by an explicit task set to detect color differences.

While the results of Experiment 1 demonstrate that form similarity amongst the moving items is not critical for the negative color effect to occur, the role of similarity in form between the target and the static distractors remains to be investigated. It may be that the attentional weight assigned to the static distractors on the basis of movement must be reduced to compensate for the high weight assigned on the basis of form. Future experiments will explore if the negative color effect holds when the target does not share form with the static distractors.

The whole set of results are best accounted for within framework that incorporates aspects of both the DW variant of GS and AET. Such a framework will allow for flexible selection mechanisms, including both negative biases against irrelevant (and associated) items, and positive biases towards relevant items, including biases towards second order *differences* in feature values in addition to feature values per se, as proposed by DW (e.g. Weidner & Müller, 2013). From AET we have the principle of weight linkage, such that when a feature in this case color is not explicitly task relevant, the default assumption is that items appearing in the color of the static distractors are also likely to be distractors. From the DW variant of GS we have the principle that top-down biases towards differences in a particular dimension known to be task relevant, can override these default linkages. Weight linkage for color and motion dominates when the dimensional weight assigned to color is low, increasing the dimensional weight assigned to the color dimension can override this linkage. Determining which other principles must accompany these core mechanisms in order to provide a full account of search and selection will require further research.

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Table 1: Experiment 1 percentage error.

	Target Color Non-singleton		Target Color Singleton	
	6 moving items	12 moving items	6 moving items	12 moving items
Half-Set	1.94	2.78	0.56	2.22
Motion Segmentation	2.22	1.94	1.39	0.83

Table 2: Experiment 2A percentage error.

	Target Color Non-singleton		Target Color Singleton	
	6 moving items	12 moving items	6 moving items	12 moving items
Half-Set	1.67	1.94	3.06	3.33
Motion Segmentation	1.67	2.50	2.50	1.94
	12 moving items	24 moving items	12 moving items	24 moving items
Full-Set	1.39	1.94	1.94	2.22

Table 3: Experiment 2B percentage error.

	Target Color Non-singleton		Target Color Singleton	
	6 moving items	12 moving items	6 moving items	12 moving items
Half-Set	2.64	2.36	5.00	3.06
Motion Segmentation	3.06	3.06	4.31	10.00

Figure 1: Example stimulus display for a color singleton trial in the motion segmentation condition of Experiment 1, arrows indicate motion, grey levels indicate color.

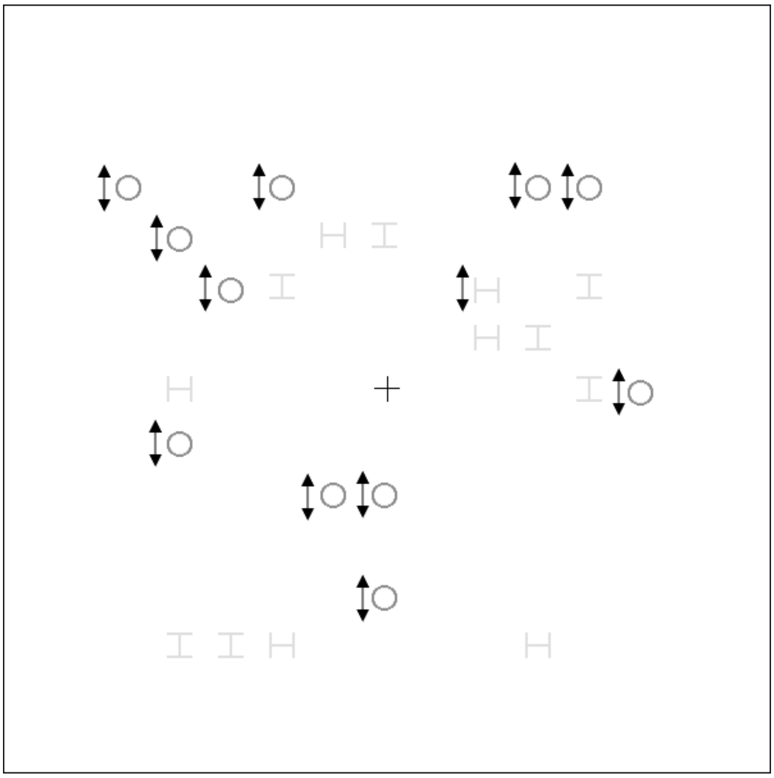

Figure 2: Search response time (RT) in Experiment 1 as a function of condition (separate lines), number of moving items (horizontal axis), and target color (left vs. right panel). The target color non-singleton cases are shown in the left panel, and target singleton cases in the right panel. Error bars show standard errors of the means.

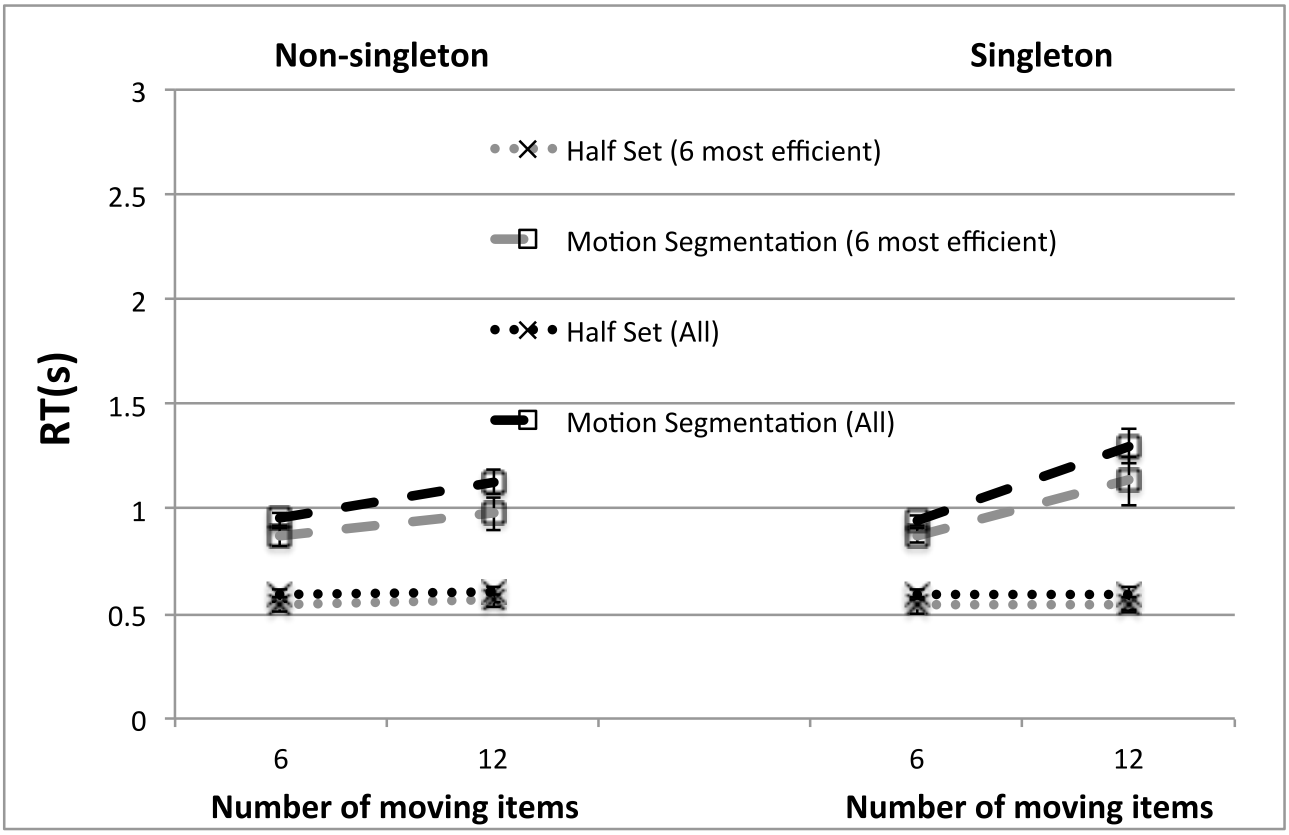

Figure 3: Scatterplot of the relationship between conjunction search efficiency and the efficiency cost related to the presence of a color singleton in the moving group. Solid line shows linear regression line.

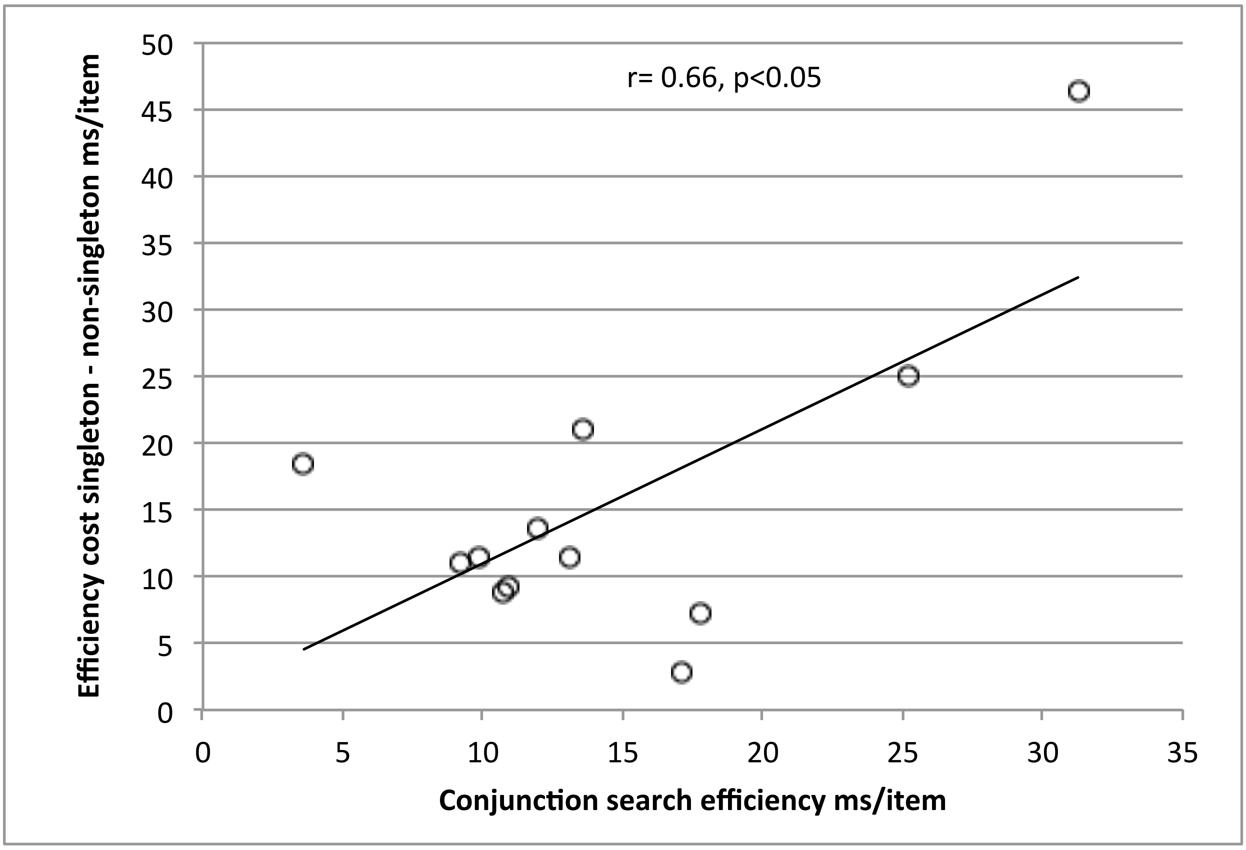

Figure 4: Example stimulus display for a color singleton trial in the motion segmentation condition of Experiment 2, arrows indicate motion, grey levels indicate color.

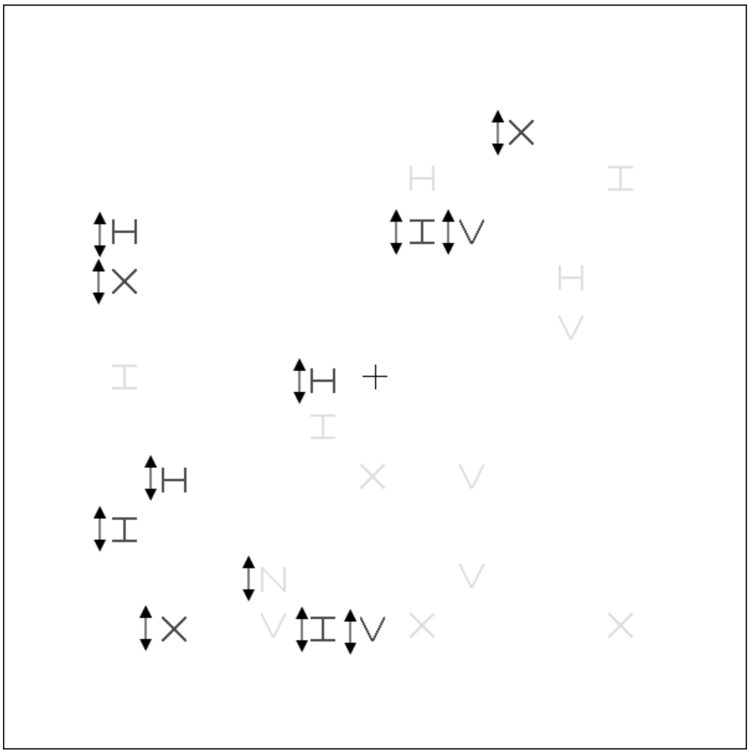

Figure 5: Search response time (RT) in Experiment 2A as a function of condition (separate lines), set size in the motion segmentation condition (horizontal axis), and target color (left vs. right panel). Note that set size in the half-set condition is half of the value indicated. The target color non-singleton cases are shown in the left panel, and target singleton cases in the right panel. Error bars show standard errors of the means.

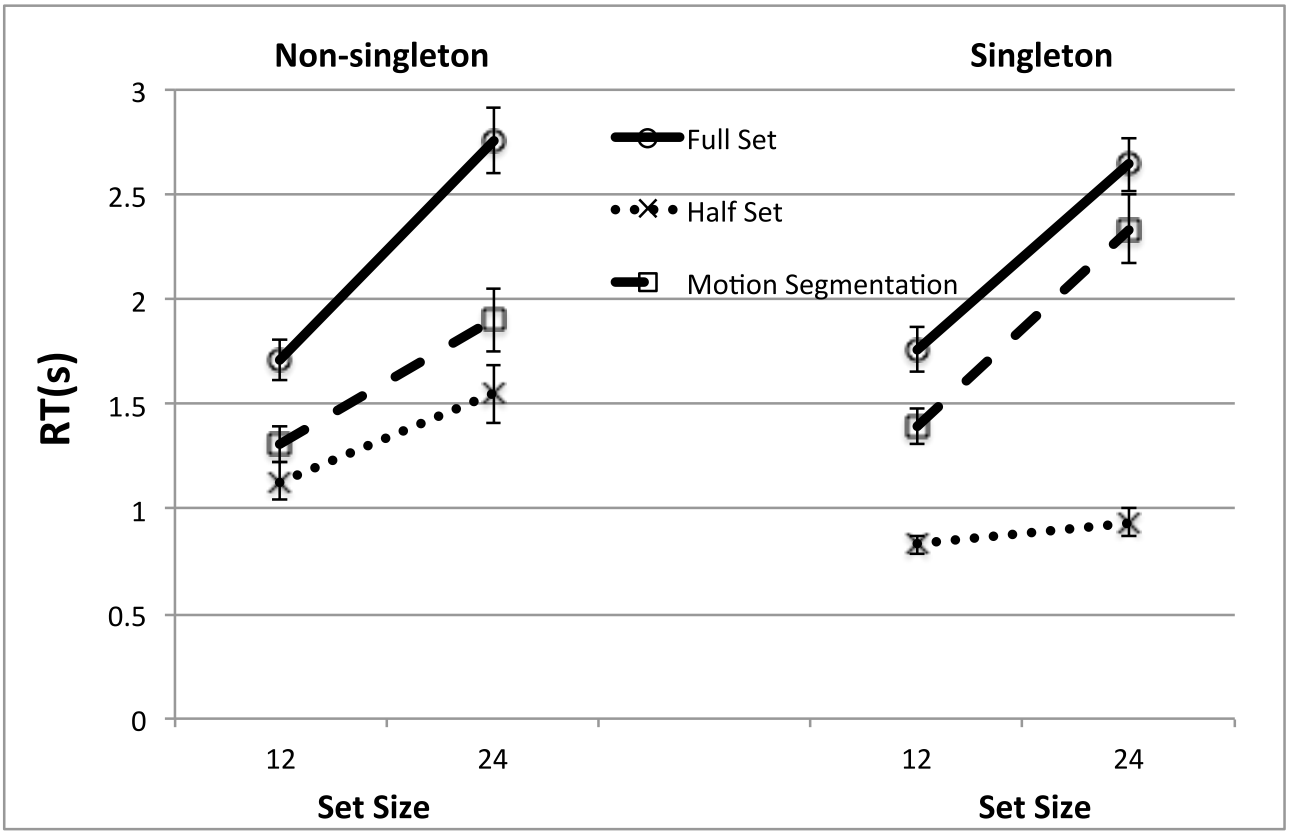

Figure 6: Search response time (RT) in Experiment 2B as a function of condition (separate lines), number of moving items (horizontal axis), and target color (left vs. right panel). The

target color non-singleton cases are shown in the left panel, and target singleton cases in the right panel. Error bars show standard errors of the means.