Inhibitory guidance in visual search: The case of movement–form conjunctions

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Abstract We used a probe-dot procedure to examine the roles of excitatory attentional guidance and distractor suppression in search for movement–form conjunctions. Participants in Experiment 1 completed a conjunction (moving X amongst moving Os and static Xs) and two single-feature (moving X amongst moving Os, and static X amongst static Os) conditions. “Active” participants searched for the target, whereas “passive” participants viewed the displays without responding. Subsequently, both groups located (left or right) a probe dot appearing in either an occupied or an unoccupied location. In the conjunction condition, the active group located probes presented on static distractors more slowly than probes presented on moving distractors, reversing the direction of the difference found within the passive group. This disadvantage for probes on static items was much stronger in conjunction than in single-

feature search. The same pattern of results was replicated in Experiment 2, which used a go/no-go procedure. Experiment 3 extended the go/no-go procedure to the case of search for a static target and revealed increased probe localisation times as a consequence of active search, primarily for probes on moving distractor items. The results demonstrated attentional guidance by inhibition of distractors in conjunction search.

Keywords Visual search · Grouping · Segmentation · Inhibition

Experiments examining the relative ease with which observers detect targets amongst distractors in search have provided important constraints on theories of vision and attention (see Wolfe, 1998a, for a review). According to the influential feature integration theory (Treisman & Gelade, 1980), if targets differ from distractors by a basic feature such as colour (e.g., Treisman & Gelade, 1980), orientation (e.g., Wolfe, Friedman-Hill, Stewart, & O’Connell, 1992), or motion (e.g., Dick, Ullman, & Sagi, 1987), they are detected easily (regardless of the number of distractors), courtesy of a set of dedicated feature maps that signal the presence of various features without the need for attention. In contrast, conjunctive targets, defined by combinations of basic features (e.g., a green N amongst brown Ns and green Xs), require the serial deployment of spatial attention to their locations in order to correctly bind the features. This produces large costs on response times (RTs) as the number of distractors increases.

Reports of efficient detection of conjunctions of colour and form (Wolfe, Cave, & Franzel, 1989), motion and form (McLeod, Driver, & Crisp, 1988), and stereoscopic depth with colour or motion (Nakayama &

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Silverman, 1986) provide a serious challenge to this account. While some theorists have put forward stimulus-specific accounts of efficient search that attribute efficient search to bottom-up aspects of perceptual processing (e.g., to a motion filter; see below), others have accommodated such results by proposing general, top-down guidance of attention based on (a) excitatory activation from target features, (b) inhibition from distractor features (see Treisman & Sato, 1990; Wolfe et al., 1989), or (c) a combination of the two (e.g., Driver, McLeod, & Dienes, 1992). How these different forms of attentional guidance operate for different features remains poorly understood, however. Here we examine how top-down attentional guidance operates in the case of movement–form conjunctions.

Filtering by motion

McLeod et al. (1988) first demonstrated that search for a target defined by a conjunction of motion and form (e.g., a moving X amongst moving Os and static Xs) was highly efficient. Additionally, they showed that search for a moving letter target amongst other moving letters was unaffected by the similarity in form of the target to a set of static distractors, consistent with the static items being filtered from search by virtue of motion. McLeod, Driver, Dienes, and Crisp (1991) further showed that it was easy to divide attention over two motion groups differing in direction whilst excluding stationary items, but difficult to divide attention over moving and stationary items whilst excluding items moving in a different direction. These findings indicate that the presence versus absence of motion takes precedence over motion's specific direction in the context of attentional guidance.

To account for these data, McLeod et al. (1988) proposed that moving stimuli could be filtered because these items selectively activated cortical area MT, an area with a specialisation for processing motion. For example, moving targets may be selected from static distractors based on read-out from MT, and search for such targets will be efficient and spatially parallel, provided that neurons in the motion-specific region differentiate between moving target and distractor forms (McLeod et al., 1988; see also Driver & McLeod, 1992). On this view, movement–form conjunctions may be detected efficiently even without top-down guidance of search, from differential bottom-up activation of MT. If the motion filter hypothesis is correct, and movement–form targets are detected by virtue of bottom-up processing, then the general consequences for the deployment of attentional resources are few. Certainly, after the target is detected there may not be lingering aftereffects of selection. Whether this is the case has never been tested.

To investigate the consequences of processing motion–form conjunctions for general attentional resources, we used a probe-dot procedure. After search was completed, all movement ceased¹ and a probe could appear either close to a distractor or in an empty region of space. RTs to the probe dot should provide an index of how prior search causes attentional-processing resources to be distributed. According to a pure bottom-up account (see McLeod et al., 1988), responses to probes appearing at the location of distractors may be unmodulated by search, or at least, any modulation should be no larger in conjunction than in feature search. However it remains possible that attentional resources may be deployed on the basis of the motion filter (e.g., McLeod et al., 1991), which would convey some advantage for probes presented at the locations of previously moving distractors when the comparison is made to probes appearing on static distractors.

The Guided Search model

Although McLeod et al. (1988) demonstrated that search for motion–form conjunctions could be detected in parallel with negligible costs of increasing the number of distractors (e.g., target-present slopes of 3 ms/item), subsequent studies have found somewhat less efficient search, with modest but significant search slopes (e.g., von Mühlenen & Müller, 1999, 2000; 12 ms/item). Relatively efficient search, with slopes in the region of 12 ms/item, is unlikely to result from preattentive pop-out or from item-by-item serial search, but may best be characterised as search that is guided by featural differences. Once cast as relatively efficient rather than parallel, motion–form conjunction search becomes a member of a broader class of search tasks that allow for guidance—including other conjunction searches, where strong featural differences provide a basis for guidance (including colour–form conjunctions: Wolfe et al., 1989; see also Wolfe, 1998b, for further discussion and analysis).

The Guided Search model (see Wolfe, 1994, 2007; Wolfe et al., 1989) provides an explicit framework for understanding excitatory guidance in search. In this model, search is guided by top-down increased weighting of features belonging to expected targets, which gives items with these features a competitive advantage over other stimuli. Activity from feature maps is weighted and summed in a master map of locations, with the location for the target receiving most support, as the target contains all relevant, highly weighted features. This model predicts that distractors sharing target

¹ Probes were presented after motion offset in order to minimise any stimulus-driven contribution of both benefits from automatic attention capture and costs from retinal smearing

features should be activated, and hence probes appearing at these locations may benefit relative to probes at background locations. Unlike the motion filter account, however, Guided Search does not hold that motion is necessarily special. With a movement–form conjunction, this means that distractors sharing their form as well as those sharing their motion with targets may be activated.

In prior studies of search for colour–form targets (e.g., Kim & Cave, 1995; see also Zenon, Ben Hamed, Duhamel, & Olivier, 2008), evidence from probe detection has indicated that both features make a contribution to search guidance, with colour being dominant. For example, responses to probes presented on distractors sharing either their colour or their form with a target are advantaged as compared to responses to probes presented on distractors sharing neither feature. Note that, at least in Kim and Cave's case, probes were presented on a blank screen after the search array had disappeared, suggesting that the biasing effects of search can continue even after the critical biasing feature has been removed.

It should be acknowledged, however, that top-down guidance in the context of Guided Search is flexible. Thus, although motion and form could be equally weighted, it is also certainly possible that more weight might be given to the dimension of motion over the form dimension (see Müller, Heller, & Ziegler, 1995). In the extreme, when high weight is placed on motion and low weight on form, the search system could be configured top down as a motion filter (see McLeod et al., 1991).

Friedman-Hill and Wolfe (1995) presented further evidence that search is guided by excitatory biases, at least in the case of colour. They showed that varying the number of searched-for colours had a much more debilitating effect on search than did corresponding variations in the number of ignored colours. This is consistent with top-down guidance of search to each potential target colour. Other studies (e.g., Brawn & Snowden, 1999; Shih & Sperling, 1996) have shown that, relative to a neutral condition in which the target was equally likely to be one of two colours, significant benefits for target discrimination may occur when the target is more likely to be of one particular colour (or size). In the case of moving stimuli, White and Carrasco (2011) found evidence for facilitatory processing of spatially distal stimuli that share an expected motion property, showing reduced motion coherence thresholds for stimuli that shared direction with the target. These facilitatory effects are consistent with excitatory guidance of attention by features towards target locations.

Neurophysiological evidence also supports the idea that attention to a particular feature value can increase sensitivity to stimuli that carry that value. Single-cell recording experiments (see Maunsell & Treue, 2006, for a review) have shown that, when a monkey attends to a stimulus with a

particular feature value, ignored stimuli presented at different locations but sharing that stimulus value enjoy increased responses in neurons tuned to their values. Direct evidence from search in monkeys (Bichot, Rossi, & Desimone 2005) also demonstrates that neural responses to distractors sharing features with a sought-for target are increased. EEG (e.g., Zhang & Luck, 2009) and fMRI (e.g., Saenz, Buracas, & Boynton, 2002) studies have also revealed increased responses to spatially distal irrelevant stimuli as a consequence of attention in the feature domain, consistent with guidance by feature activation.

Inhibitory segregation

In contrast to accounts of search by excitatory guidance, other accounts propose that there can be inhibition of distractor features. For example, Treisman and Sato (1990) argued that conjunction targets could be found efficiently if distractors could be selectively inhibited. This selective inhibition could operate if the features of distractors are sufficiently different from those of targets.

Substantial evidence supports the involvement of inhibitory guidance in search. Trial-by-trial priming effects reveal substantial costs when new targets take on the feature values previously held by distractors, at least in the case of colour and form (e.g., Koshino, 2001). Probe studies of feature search also reveal that, when appropriate comparisons are made between probes presented on distractors and those presented on a blank background, there is a cost for probes presented on the distractor (Cepeda, Cave, Bichot, & Kim, 1998; Müller, von Mühlenen, & Geyer, 2007) specifically under conditions of active search. Additionally, it is important to note that the studies above that have shown facilitation of target detection contingent on target knowledge (e.g., Brawn & Snowden, 1999; Shih & Sperling, 1996) also revealed negative effects on invalid trials when on a minority of trials targets appeared with unattended features. This is consistent with a contribution to search from the suppression of distractors.

Watson and Humphreys (1997, 2000) have also argued that distractors may be selectively inhibited if their temporal properties differ from those of the target. These authors used a preview search procedure in which one set of distractors appeared prior to the onset of the target and new distractors. Provided that the temporal interval was 400 ms or longer, the old distractors had little impact on search. Humphreys, Jung Stalmann, and Olivers (2004; see also Braithwaite, Humphreys, Hulleman, & Watson, 2007; Braithwaite, Humphreys, Watson, & Hulleman, 2005) used a probe-dot procedure to measure attentional allocation in

preview search and found that probes on old distractors were difficult to detect when measured relative to probes on the background. This evidence, consistent with distractor inhibition, occurred only when probe detection was embedded in a search task; there was no evidence for inhibition of old distractors when probe detection was the primary task.

Using fMRI, Allen, Matthews, and Humphreys (2008; see also Olivers, Smith, Matthews, & Humphreys, 2005) demonstrated that distractor inhibition in preview search was associated with activation of superior parietal cortex and precuneus. Interestingly, Dent, Allen, and Humphreys (2011) have further demonstrated that not only are overlapping brain regions recruited when participants perform preview and motion–form search tasks, but activation in these overlapping regions increases when the temporal and motion cues are used to make search efficient by segmenting relevant items from irrelevant distractors. This fits with the idea that common processes of distractor inhibition may be involved in preview and motion–form search. Indeed, damage to posterior parietal cortex disrupts both preview search (Humphreys, Olivers, & Yoon, 2006; Olivers & Humphreys, 2004) and search for movement–form conjunctions (Dent, Lestou, & Humphreys, 2010). These neuropsychological data indicate that the common brain activity found in fMRI may be *necessary* for efficient search.

If common mechanisms of distractor inhibition mediate motion–form as well as preview search, it follows that probe detection results should emerge with motion–form search that are similar to those found in preview search. That is, probes appearing on static distractors should be difficult to detect when participants search for a moving–form target, while probes appearing on moving distractors should suffer when search is for a static–form target. Also, following the experiments on probe detection in preview search, these effects may be confined to when probe detection is embedded in search; the dynamic properties of the search stimuli should not matter when probe detection is the primary task. Such a result would indicate a top-down component in inhibitory filtering, and that effects are not due solely to the bottom-up properties of the displays.

The present study

To assess the mechanisms mediating search for movement–form targets, we used a probe-dot procedure that was performed either as the primary task or as a subsidiary task embedded in a search procedure (see also Müller et al., 2007). In Experiments 1 and 2, participants searched for targets defined as conjunctions

of motion and form (a moving X amongst moving Os and static Xs). Subsequent to the search response, participants were presented with a probe dot that they had to locate. Just before the probe appeared, all of the objects stopped moving, so that they were stationary at the time that the probe appeared. The probe dot appeared either on a previously moving distractor (moving O) or nonmoving distractor (static X). We predicted that responses to the probe would reflect the attentional priority assigned to particular locations in space. To isolate the processes specific to active conjunction search, participants also performed feature search tasks in which all objects shared motion, and active search was contrasted with passive search in which only the probe and not the search task was performed. In a third experiment, we examined search for a static target, in order to explore any potential asymmetry for moving and static targets.

Experiment 1: Present/absent search

Method

Participants

A group of 24 undergraduate or postgraduate students from the University of Birmingham took part in the study in return for either course credit or payment of £4. Participants were randomly assigned to one of two groups. These were the “active” viewing group and the “passive” viewing group (12 participants in each). The active group had a mean age of 23.7 years (range 19–32) and contained 3 left-handed participants, 5 males overall. The passive group had a mean age of 22.6 years (range 18–32) and contained 1 left-handed participant, 5 males overall.

Equipment

The experiment was controlled by programs written with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and MATLAB 7.2. Stimuli were displayed on a ViewSonic p225f 21-in. monitor (120 Hz), driven by a PowerMac Dual G5 equipped with an Nvidia 6600LE graphics card. Participants interacted with the computer via a standard keyboard.

Design and stimuli

Participants viewed the displays from a distance of approximately 57 cm. The stimuli were constructed from simple semicircular lines 2 pixels (0.6 mm) in width and 8.4 mm in diameter (see Fig. 1). The semicircles were combined in two possible ways: (1) by connecting the end

Fig. 1 Illustration of the paradigm. Arrows next to items indicate oscillatory motion. Arrows underneath the stimulus panels indicate the passage of time

points of two semicircles to construct a closed circular O shape, or (2) with the midpoints of two curves abutting to construct a curved X shape. In both cases, the maximum horizontal and vertical size of each item was 8.4×8.4 mm.

The stimuli were initially positioned within the centres of the cells of an 11×11 matrix of equally spaced (12.3 mm centre to centre) possible locations. Since the centre cell was reserved for the fixation cross, there were 120 equally spaced possible locations for the search items.

When present, stimulus motion took the form of a vertical oscillation (1.85 cm/s), where items moved in one direction for a maximum of 3.7 mm before abruptly changing direction and moving in the opposite direction for a maximum of 3.7 mm. The initial direction of the motion (up or down) was determined at random on a trial-by-trial basis but was always assigned uniformly for all of the moving items in the display on any given trial. On the first frame of animation, objects were presented at the extreme end of the motion path either 1.85 mm above (when initial direction was down) or below (when initial direction was up) the cell centre. The vertical distance between moving and static objects thus varied over time, with the minimum distance between any two items at any instant being 3 mm.

The probe was a white dot 2.5 mm wide. When the probe appeared on a distractor, it appeared adjacent to the contours in the centre of the lower half of the object (taking into account any position change for moving objects). This meant that the nearest contour element was equally distant from the probe for both types of distractor (see Fig. 1). When the probe appeared on the blank background, it appeared in the centre of the lower half of one of the cells of the matrix that otherwise would have contained a distractor.

Each group of participants completed three different conditions. In the conjunction condition, participants

searched for a moving X in moving Os and static Xs. In the moving single-feature condition, participants searched for a moving X in moving Os. In the static single-feature condition, participants searched for a static X in static Os. In the conjunction condition, the two distractor types were present in equal numbers when the target was absent, but the target always replaced one of the moving O distractors when it was present.

In each of the three search conditions, the probe dot could appear at a number of different locations. In the conjunction condition, the probe fell equally often on a moving distractor, a static distractor, or the blank background. In the feature conditions, the probe occurred equally often either on a distractor or on the blank background. In no case did the probe item ever appear on the target object.

The active group completed a search for the target (present on 50% of trials) before the probe appeared, whereas the passive group merely observed the displays for a duration that was fixed to the mean search time for participants in the active group (to the nearest whole frame of 8.3 ms) before responding to the probe.

Procedure

At the start of the experiment, the participants practiced each of the three conditions in turn (24 trials not included in the analysis). Participants then completed six blocks of experimental trials. They completed each of the three conditions (in an order counterbalanced over participants) in the same order twice in succession. At the start of the first three blocks (1–3), the first 24 trials were practice, and at the start of the second three blocks (4–6), the first 12 trials were treated as practice. In the conjunction condition, there were 288 experimental trials: 2 (target present/target absent) $\times$ 3 (probe location: on moving distractor/on static distractor/on background) $\times$ 2 (display size: 8/16) $\times$ 24 repetitions per trial type. In each of the feature conditions, there were 192 experimental trials: 2 (target present/target absent) $\times$ 2 (probe location: on distractor/on background) $\times$ 2 (display size: 8/16) $\times$ 24 repetitions per trial type. At the start of each block of trials, an instruction screen appeared to remind participants of the search target and the distractors for that block. Each trial then began with a blank screen for 200 ms, followed by the onset of the fixation cross and the surrounding outline box for 200 ms; the search items then appeared, and started to move immediately if appropriate.

Participants in the active group first indicated whether the target was present or absent by pressing one of two keys on the keyboard, “a” or “z,” respectively, with their left hand. As soon as the keypress was detected all motion stopped, and 60 ms later the probe dot appeared. For

Fig. 2 Experiment 1 search RTs (in seconds) as a function of display size (x-axis) and search task (separate lines). Performance for present trials is plotted separately on the left, and for absent trials on the right. Error bars show standard errors of the means

participants in the passive group, motion terminated after a fixed duration (the mean search time for the active group, to the nearest whole frame of 8.3 ms; see Fig. 1), and after 60 ms the probe appeared. The probe dot appeared equally often on the left and right sides of the screen. Participants responded to the location of the probe dot by pressing “n” (left) or “m” (right) with the index and middle fingers of the right hand to indicate the location. Following the location response, the next trial commenced.

Results

Search

All incorrect RTs (3%) and RTs more than 3SDs from the mean (1.9%) were removed. Figure 2 illustrates the mean values, and Table 1 shows the search slopes in each condition. An ANOVA with the factors of task (conjunction vs. moving feature vs. static feature), target presence (present vs. absent), and display size (8 vs. 16) revealed a significant three-way interaction between all of the factors $F(2, 22) = 11.967$, $p < .005$, indicating stronger effects of display size in the conjunction task, especially for absent trials. Indeed, removal of the conjunction condition eliminated this interaction, $F < 1$, and when the feature conditions were considered alone there was no significant

effect of task or display size, nor any significant interaction, all F s < 1 , indicating highly efficient performance across the board. In contrast, in the conjunction condition there was a significant interaction between target presence and display size, $F(1, 11) = 17.148$, $p < .005$. There were significant effects of display size in both the present and absent trials [$F(1, 11) = 32.155$, $p < .0001$, and $F(1, 11) = 32.909$, $p < .0001$, respectively], but the effect was larger for absent than for present trials. However, although performance was less efficient in the conjunction than in the feature conditions, performance for present trials was still relatively efficient even in the conjunction condition (slope = 12.4 ms/item).

Probe detection

Probes following conjunction search Errors (2.5%) and RTs more than 3SDs from the mean were removed (2.2%), and for the active group, trials with errors on the search task were also removed (an additional 2.9% of responses). Figure 3 illustrates the mean RTs. The RTs were first entered into a four-factor mixed measures ANOVA with the factors group (active vs. passive), target presence (present vs. absent), probe location (moving distractor vs. static distractor vs. background), and display size (8 vs. 16 items).

There was a main effect of probe location, $F(2, 44) = 20.823$, $p < .0001$; in general, probes presented on distractors were responded to more slowly than probes on the background. There was also a significant effect of group, $F(1, 22) = 16.074$, $p < .001$, driven by globally slower RTs in the active than in the passive group. There were also main effects of target presence, $F(1, 22) = 6.525$, $p < .05$, and display size, $F(1, 22) = 19.635$, $p < .0001$. These effects were qualified by three-way interactions with target presence, probe location, and group, $F(2, 44) = 3.384$, $p < .05$, and display size, probe location, and group, $F(2, 44) = 5.967$, $p < .005$. The results are thus consistent with larger effects of probe location in the active group that were exaggerated both on target-absent trials and at the higher display size; this is consistent with a top-down contribution and inconsistent with the bottom-up version of the motion filter. The interactions were decomposed by analysing the data for each group separately.

Table 1 Search slopes (in milliseconds/item) for each search task

	Conjunction	Moving Feature	Static Feature
Experiment 1: Present	12.4	−1.1	−1.1
Experiment 1: Absent	40.2	2.7	−2.3
Experiment 2: Moving target	18.1	2.7	1.5
Experiment 3: Static target	29.2	2.3	2.1

Fig. 3 Experiment 1 RTs (in seconds) for probes following conjunction search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. For each group, present trials are plotted separately on the left, and absent trials on the right. Error bars show standard errors of the means

Passive group (bottom-up effects) There was a significant main effect of probe location, $F(1, 11) = 20.916$, $p < .0001$: Probes on static objects were localised more slowly than probes on the blank background, $F(1, 11) = 15.702$, $p < .005$, and probes on moving objects were in turn detected more slowly than probes on static objects, $F(1, 11) = 5.092$, $p < .05$. In terms of bottom-up processing, probes were easier to detect on static than on moving objects.

Active group (bottom-up plus top-down effects) There were main effects of target presence, $F(1, 14) = 7.278$, $p < .05$, display size, $F(1, 14) = 22.814$, $p < .001$, and probe location, $F(2, 28) = 15.444$, $p < .0001$. Probe location interacted with both display size, $F(2, 28) = 8.761$, $p < .005$, and target presence $F(2, 28) = 4.615$, $p < .05$.

Separate analyses of present and absent trials revealed that the effect of probe location was significant for both the present, $F(2, 22) = 10.724$, $p < .005$, and the absent, $F(2, 22) = 17.145$, $p < .0001$, trials. For absent trials, probes on moving objects were detected more slowly than probes on the background, $F(1, 11) = 18.245$, $p < .001$, particularly at the larger display size [$F(1, 11) = 6.601$, $p < .05$, for the probe location $\times$ display size interaction]. Probes on static objects were localised even more slowly than probes on moving objects, $F(1, 11) = 12.453$, $p < .05$, but there was no interaction with display size, $F = 1.057$, $p = .326$.

For present trials, probes on moving objects were localised more slowly than probes on the background, $F(1, 11) = 19.713$, $p < .001$; there was no interaction with display size, $F(1, 11) = 1.621$, $p < .229$. Probes on static items were localised more slowly than probes on moving items at the larger display size [$F(1, 11) = 7.802$, $p < .05$, for the probe location $\times$ display size interaction].

The bottom-up advantage for probes on static items noted above was not present for the active group; in

contrast, they displayed a disadvantage for static items, consistent with inhibitory segregation, but inconsistent with guided search or with the motion filter.

Direct comparisons of the active and passive groups (the effect of active search) To directly test the different predictions of the hypotheses regarding the effects of active search on probe detection, we compared the effects of active and passive viewing directly. The probe location $\times$ group interaction was significant for comparisons of probes on static items against the background, $F(1, 22) = 11.031$, $p < .005$, but not for the comparison of probes on moving objects against the background, $F < 1$. The effect of active viewing was to increase the cost for probes on static items. Thus, the attentional modulations seen in conjunction search were inhibitory, contingent on active search, and feature-specific, as predicted by the inhibitory segregation hypothesis.

Probes following feature search Below are the results for probes that appeared after search for single features.

Moving feature search Errors (2.9%) and RTs more than 3 SDs from the mean were removed (an additional 2%), and for the active group trials with errors on the search task were also removed (an additional 2.2% of responses). Figure 4 illustrates the mean RTs. There were main effects of target presence, $F(1, 22) = 5.562$, $p < .05$, probe location, $F(1, 22) = 38.954$, $p < .0001$, and group, $F(1, 22) = 13.056$, $p < .005$. RTs were faster to probes on absent trials for the passive relative to the active group, and for probes on the background. None of the interactions involving probe location or group approached significance, $F < 1$.

Fig. 4 Experiment 1 RTs (in seconds) for probes following moving feature search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. For each group, present trials are plotted separately on the left and absent trials on the right. Error bars show standard errors of the means

Static feature search Errors (2.9%) and RTs more than 3 SDs from the mean were removed (additional 1.9%), and for the active group trials with errors on the search task were also removed (an additional 2.3% of responses). Figure 5 illustrates the mean RTs. There were significant main effects of probe location, $F(1, 22) = 12.94$, $p < .005$, and group, $F(1, 22) = 9.86$, $p < .005$. Probe location and group interacted, $F(1, 22) = 4.308$, $p < .05$, as did target presence, probe location, and display size, $F(1, 22) = 8.923$, $p < .01$. The cost for probes on the background only differed reliably as a function of group for absent trials [$F(1, 22) = 1.908$, $p = .181$, and $F(1, 22) = 7.837$, $p < .01$, for the probe location $\times$ group interaction on present and absent trials, respectively], and then only for 16 and not 8 items [$F(1, 22) = 9.586$, $p < .005$, and $F(1, 22) = 2.665$, $p = .117$, for the probe location $\times$ group interaction on absent trials with 16 and 8 items, respectively].

Comparisons of probes following active feature and conjunction search (the effect of search task) For the active group, we assessed the relative sizes of the costs for probes on distractors in the conjunction and feature conditions. Recall that the bottom-up motion filter account predicts similar performance in conjunction and feature search, whereas the other hypotheses predict greater top-down modulation of conjunction search. For probes on static distractors, there was a significant interaction between task and probe location, $F(1, 11) = 14.894$, $p < .005$, indicating a greater cost for probes on distractors in conjunction than in feature search. This is consistent with increased negative top-down modulation of distractors in conjunction search, as predicted by the inhibitory segregation hypothesis. When the probe appeared on the background, responses were made equally quickly for both groups, $F(1, 11) = 1.859$, $p = .2$. For probes on moving objects, the task $\times$ probe location interaction did not achieve

significance, $F(1, 11) = 3.19$, $p = .102$; any costs for probes on moving items relative to the background were equal across the active and passive viewing tasks.

Discussion

The results of the search task showed that single features could be detected in parallel, with negligible slopes. In contrast conjunction search, while relatively efficient, was not parallel, since there were modest but significant increases in RTs with increasing numbers of distractors. The search slopes we observed are consistent with previous reports by Müller and von Mühlenen (1999, 2000) of relatively efficient search. These results indicate that conjunctions of motion and form do not pop out effortlessly in the same way that single features do. However it is also the case that search was more efficient than the 20–30 ms/item typical of serial searches (see Wolfe, 1998a, 1998b).

The probe detection results showed that the efficiency of probe localisation varied as a function of probe location and task. When participants viewed the search stimuli passively before responding to the probe, RTs were slower overall when the probe appeared on an item than when it fell on the background, and this effect was most pronounced for probes on moving items. These effects may reflect masking of the probe dot by the search items. Moving items may provide more powerful masking than static items due to retinal smearing.

In the active group, a very different pattern of results held. In this case, the active group showed a large cost for probes appearing on static objects, both relative to the background and relative to probes on moving objects. In general, this cost was larger at the larger display size and for absent trials. There was no evidence of any differential modulation of probe detection on moving items as a function of passive versus active group. Although there was some evidence for costs when participants actively searched static feature displays (see also Cepeda et al., 1998; Müller et al., 2007), the effect in conjunction search was much larger. Thus, the major consequence of active conjunction search was to induce a large cost for probes presented on static objects, consistent with active suppression of locations containing nontarget features.

However, there are some reasons to be cautious. Firstly, overall RTs for present trials were quite long for conjunction search (around 1 s). Secondly, there was a gross difference in overall RTs in the probe task between the active and passive participants. Such overall differences make interpretation of task differences difficult. In Experiment 2, we sought to replicate the result, but using a go/no-go procedure to simplify the search task. In

Fig. 5 Experiment 1 RTs (in seconds) for probes following static feature search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. For each group, present trials are plotted separately on the left and absent trials on the right. Error bars show standard errors of the means

Experiment 2, participants simply responded to the presence of the search target. We predicted that by substantially simplifying the response requirement, we would speed overall RT, allowing for both a cleaner assessment of probe detection after fast responses and the generation of a comparison in which active and passive groups were more closely matched for overall RT.

Experiment 2: Go/no-go

Method

Participants

Two groups (active/passive) of 15 participants from the University of Birmingham took part in return for course credit. The active group—mean age 19.3 years (range 18–20), 1 left-handed participant, and 2 males—responded to both the search and the probe tasks. The passive group—mean age 18.9 years (range 18–21), 3 left-handed participants, and 3 males—responded only to the probe.

Equipment, stimuli, design, and procedure

The method was as in Experiment 1, with the following exceptions: In the active group, for present trials motion was terminated by pressing the “a” key on the keyboard to indicate target detection (no time limit), and the probe dot then followed 60 ms later. Absent trials terminated after 1,500 ms or a false alarm response. No probe was presented on absent trials. The passive group were only exposed to the target-present trials, with target-absent trials omitted.

Fig. 6 Experiment 2 target-present search RTs (in seconds) as a function of display size (x-axis) and search task (separate lines). Error bars show standard errors of the means

Results

Search RT

Miss errors were not possible, since there was no time limit on responding, so that present trials were always eventually terminated by a correct present response. Errors could only be generated by participants making false alarms on absent trials. The frequency of false alarms was low (<1%). RTs more than 3SDs from the mean (1.8%) were removed. Figure 6 illustrates the pattern of mean RTs, and Table 1 summarises the search slope values for each condition.

There was a significant effect of search task, $F(2, 28) = 95.218$, $p < .0001$, with slower performance in the conjunction task. There was also an effect of display size, $F(1, 14) = 57.021$, $p < .0001$, that was qualified by an interaction with task, $F(2, 28) = 33.061$, $p < .0001$, consistent with larger effects of display size in the conjunction condition (18.1 vs. 2.7 and 1.46 ms/item). For the feature conditions, there was a significant effect of display size, $F(1, 14) = 20.466$, $p < .0001$, but no interaction, $F < 1$, indicating that performance was equally efficient in both moving and static feature cases.

Probe RT

Probes following conjunction search Incorrect RTs (3.2%) and RTs more than 3SDs from the mean (a further 2.1%) were removed. Figure 7 illustrates the pattern of mean RTs. There was no significant effect of group, $F(1, 28) = 1.35$, $p = .26$, but there were main effects of probe location, $F(2, 56) = 37.354$, $p < .0001$, and display size, $F(1, 28) = 8.992$, $p < .001$, both of which were qualified by interactions with group [probe location $\times$ group, $F(2, 56) = 6.31$, $p < .005$, and display size $\times$ group, $F(2, 56) = 13.767$, $p < .001$], consistent with both larger effects of probe location and display

Fig. 7 Experiment 2 RTs (in seconds) for probes following conjunction search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. Error bars show standard errors of the means

size in the active group. Separate analyses of group were used to decompose these interactions (see below). In contrast to Experiment 1, and despite the trend visible in Figure 7 towards larger costs for probes on static distractors at 16 items in the active group, neither the interaction between display size and probe location, $F(2, 56) = 2.624$, $p = .081$, nor the three-way interaction between all of the factors, $F(2, 56) = 1.451$, $p = .243$, reached statistical significance.

Passive group (bottom-up effects) There was a main effect of probe location, $F(2, 28) = 14.943$, $p < .0001$. Probes on static distractors were responded to more slowly than probes on the background, $F(1, 14) = 16.352$, $p < .001$, and probes on moving items were responded to even more slowly than probes on static items, $F(1, 14) = 6.897$, $p < .05$. There was again a bottom-up advantage for probes on static as compared to moving distractors.

Active group (bottom-up plus top-down effects) There was a main effect of probe location, $F(2, 28) = 27.212$, $p < .0001$. Probes on moving distractors were responded to more slowly than probes on background locations, $F(1, 14) = 60.871$, $p < .0001$, and probes on static distractors were responded to more slowly than probes on moving distractors, $F(1, 14) = 6.099$, $p < .05$. There was also a main effect of display size, $F(2, 28) = 16.784$, $p < .0001$, with generally slower responses at the higher display size. The interaction between display size and probe location did not reach significance, $F(2, 28) = 3.068$, $p = .062$. In contrast to the passive group, for the active group, there was a cost for probes on static as compared to moving distractors. This result is consistent with top-down suppression of static items, as predicted by the inhibitory segregation hypothesis.

Direct comparisons of the active and passive groups (effect of active search) Direct comparisons between the groups failed to show any difference in the cost for probes on moving distractors relative to the background, $F < 1$. However the probe location $\times$ group interaction was significant when probes on static items were compared to either the background, $F(1, 28) = 7.733$, $p < .01$, or to probes on moving objects, $F(1, 28) = 11.649$, $p < .01$. Active viewing increased the cost for probes on static items, whilst leaving the cost for moving items relative to the background constant. This pattern of results is only predicted by the inhibitory segregation hypothesis.

Probes following feature search The results for probes that followed single-feature search were as follows.

Moving feature search Incorrect RTs (3.1%) and RTs > 3 SDs from the mean (a further 2.1%) were removed.

Figure 8 illustrates the mean RTs. There was only a main effect of probe location, $F(1, 28) = 39.45$, $p < .0001$, with slower localisation of probes on distractors relative to the background.

Static feature search Incorrect RTs (3.1%) and RTs > 3 SDs from the mean (a further 1.8%) were removed. Figure 9 illustrates the mean RTs. There was a main effect of probe location, $F(1, 28) = 12.278$, $p < .005$, with slower detection of probes on distractors than on the background. Probe location also interacted with display size, $F(1, 28) = 5.93$, $p < .05$: There was an effect of display size for probes on static distractors, $F(1, 28) = 5.514$, $p < .01$, but not for probes on the background, $F < 1$.

Comparisons of probes following active feature and conjunction search (the effect of search task) For the active group, an additional analysis assessed the relative sizes of the costs for probes on distractors in the conjunction and feature tasks. For probes on static distractors, there was a significant interaction between task and probe location, $F(1, 14) = 20.542$, $p < .0001$; the cost was larger in the conjunction task. For probes on moving objects, the task $\times$ probe location interaction was not reliable, $F(1, 14) = 1.361$, $p = .263$, with the costs for the active group approximately equal, regardless of probe location. Increased costs specific to static items in conjunction search are predicted only by the inhibitory segregation hypothesis.

Discussion

The results of Experiment 2 were consistent with those of Experiment 1. Again there was evidence of selective suppression of static objects that was specific to active

Fig. 8 Experiment 2 RTs (in seconds) for probes following moving feature search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. Error bars show standard errors of the means

Fig. 9 Experiment 2 RTs (in seconds) for probes following static feature search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. Error bars show standard errors of the means

conjunction search. This same pattern of results occurred despite search RTs being around 200 ms faster than in Experiment 1 and clearly less than 1 s in duration. The go/no-go procedure had two further consequences: Firstly, search was slightly less efficient here, and this might be attributed to an overestimation of efficiency in the present/absent task of Experiment 1 due to the removal of miss trials, which could not occur in Experiment 2. Secondly, due to the simplification of the search response requirement, probe RTs were also speeded. This might be attributed to a generally smaller “psychological refractory period” following a simpler decision (see Pashler & Johnston, 1998). From our perspective, the positive consequence of overall speeded RTs was that the active and passive groups were very closely matched for overall RTs, ruling out any explanation of differences in terms of overall RTs and making for a better comparison of the effects of probe location across the groups.

Experiments 1 and 2 demonstrated that, when a target is amongst a moving group, the static group is inhibited. This finding is incompatible with the classic version of the motion filter hypothesis, which suggests that motion–form conjunctions may be detected preattentively (with no effects on either static or moving distractors), and also incompatible with the idea that general attentional resources are directed *towards* moving items.

In a third experiment, we sought to generalise the results from Experiments 1 and 2 by examining search for a static form target presented amongst static distractors with a different form and moving distractors sharing the target’s form. This experiment evaluates whether inhibition is applied asymmetrically, being more easily applied to static than to moving distractors (e.g. Franconeri & Simons, 2003), perhaps because of a bottom-up bias to attend to moving items, or whether reversed effects can occur (greater inhibition on moving than on static distractors, but primarily for partic-

ipants engaged in active search rather than passive viewing). The experiment also provided a test of one potential reason why there was no evidence for suppression of moving distractors in Experiments 1 and 2, which is that suppression was prevented by the change in the motion properties of the stimuli (which ceased movement before probes were presented). It is possible that participants did attempt to direct suppressive resources to moving distractors, but this was prevented by attention being cued to these distractors when they stopped moving. If there was some form of attentional capture to moving distractors, there should be no evidence in Experiment 3 for attentional suppression of these distractors in the active relative to the passive search group.

Experiment 3: Searching for a static target

Method

Participants

Two groups (active/passive) of 12 participants from the University of Birmingham took part in return for a payment of £4. The active group—mean age 22.9 years (range 19–31), 1 left-handed, and 3 males—responded to both the search and the probe tasks. The passive group—mean age 23.1 years (range 19–27), all right-handed, 4 males—responded only to the probe.

Equipment, stimuli, design, and procedure

The method was as in Experiment 2, with the following exceptions: In the conjunction condition, participants searched for a static X target amongst static O and moving X distractors. The two feature conditions were as in Experiment 2.

Results

Search RT

Errors could be generated by participants making false alarms on absent trials. The frequency of false alarms was low (<1%). RTs more than 3SDs from the mean (1.9%) were removed. Figure 10 illustrates the pattern of mean RTs, and Table 1 summarises the search slope values for each condition.

There was a significant effect of search task, $F(2, 22) = 150.53$, $p < .0001$, with slower performance in the conjunction task. There was also an effect of display size, $F(1, 11) = 101.451$, $p < .0001$, that was qualified by an interaction with task, $F(2, 22) = 63.834$, $p < .0001$, consistent

Fig. 10 Experiment 3 target-present search RTs (in seconds) as a function of display size (x-axis) and search task (separate lines). Error bars show standard errors of the means

with larger effects of display size in the conjunction condition (29.2 vs. 2.3 and 2.1 ms/item). For the feature conditions, there was a significant effect of display size, $F(1, 11) = 19.214$, $p < .001$, but no interaction, $F < 1$, indicating that performance was equally efficient in both moving and static feature cases.

Probe RT

Probes following conjunction search (Can moving items be inhibited?) Incorrect RTs (3.4%) and RTs more than 3SDs from the mean (a further 1.6%) were removed. Figure 11 illustrates the pattern of mean RTs.

Probes were located more slowly in the active than in the passive group, $F(1, 22) = 22.383$, $p < .0001$. The main effect of probe location was also significant, $F(2, 44) = 93.173$, $p < .0001$. Probe location and display size both interacted with group, $F(2, 44) = 10.595$, $p < .0001$, and $F(1, 22) = 5.497$, $p < .05$, respectively. The three-way interaction between group, display size, and probe location was also significant, $F(2, 44) = 4.283$, $p < .05$, consistent with larger probe location effects in the active group, especially at the higher display size. Separate analyses comparing probe location times for probes on each distractor type relative to the blank background were used to decompose the higher-order interaction.

Probes on moving items versus the blank background (inhibition of moving items?) Performance was slower overall in the active group, $F(1, 22) = 18.376$, $p < .0001$. Probes on moving distractors were responded to more slowly than probes on the background, $F(1, 22) = 102.185$, $p < .0001$. Importantly, as predicted by the inhibitory segregation hypothesis, probe location interacted with group, $F(1, 22) = 12.321$, $p < .005$; performance was slowed as a function of group much more for probes on distractors than for probes on the background. The probe

location $\times$ group $\times$ display size interaction also reached significance, $F(1, 22) = 8.488$, $p < .01$. Separate analyses of each display size showed that the group $\times$ probe location interaction was significant for both 8 items, $F(1, 22) = 7.057$, $p < .05$, and 16 items, $F(1, 22) = 14.161$, $p < .001$. The RT cost for probes on moving items relative to the background was larger in the active group, regardless of display size, but the effect was more pronounced when more distractors were present.

Probes on static items versus the blank background (inhibition of static items?) Performance was overall slower in the active group, $F(1, 22) = 22.383$, $p < .0001$. Probes on static distractors were responded to more slowly than probes on the background, $F(1, 22) = 49.235$, $p < .0001$. Probe location interacted with group, $F(1, 22) = 14.785$, $p < .001$. However, probe location also interacted with display size, $F(1, 22) = 4.846$, $p < .05$, and was involved in a three-way interaction between probe location, group, and display size, $F(1, 22) = 6.7$, $p < .05$. Separate analyses of each display size showed that group interacted with probe location at display size 16, $F(1, 22) = 20.897$, $p < .0001$, but not at display size 8, $F(1, 22) = 2.099$, $p = .161$. The RT cost for probes on static items relative to the background was larger in the active group only for 16 items. Thus, in contrast to the case of the moving items, any attentional modulation of static items was weak.

Probes following feature search The results for probes that followed single-feature search were as follows.

Moving feature search Incorrect RTs (on 2.5% of the trials) and RTs $>3SDs$ from the mean (a further 1.8% of the data) were removed. Figure 12 illustrates the mean correct RTs.

There was a main effect of group, $F(1, 22) = 17.141$, $p < .0001$, with slower responses in the active group.

Fig. 11 Experiment 3 RTs (in seconds) for probes following conjunction search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. Error bars show standard errors of the means

The effect of probe location was also significant, $F(1, 22) = 63.402$, $p < .0001$, with slower responses to probes on distractors than on the background. Although the cost for probes on distractors relative to the background was numerically larger in the active group, the small difference in cost was borderline [interaction between group and probe location: $F(1, 22) = 3.971$, $p = .059$].

Static feature search Incorrect RTs (4.1% of the data) and RTs $> 3SDs$ from the mean (a further 2.2% of the trials) were removed. Figure 13 illustrates the mean correct RTs.

There were main effects of group, $F(1, 22) = 11.384$, $p < .0001$, and probe location, $F(1, 22) = 24.543$, $p < .0001$. The active group was overall slower than the passive group, and probes were located more slowly on distractors than on the background. The interaction between probe location and group was also significant, $F(1, 22) = 4.353$, $p < .05$, indicating an increase in the cost for probes on static distractors in the active group.

Comparison of costs for conjunction and feature (the effect of search task) In a further analysis, we directly compared the magnitudes of the costs (RTs to probes on distractors – RTs to probes on background locations) as a function of task type (feature vs. conjunction) for the active and passive groups. In neither group was the overall cost for probes on static distractors modulated by task type (conjunction vs. feature search, $F_s < 1.7$). In both groups, costs for probes on moving distractors were larger in conjunction than in feature search [task type effect: $F(1, 11) = 24.588$, $p < .0001$, and $F(1, 11) = 9.26$, $p < .05$, for the active and passive groups, respectively]. Combined analysis of both groups showed that task type interacted with group due to a larger increase in the cost in conjunction versus feature search in the active relative to the passive group, $F(1, 22) = 6.7$, $p < .05$.

Fig. 12 Experiment 3 RTs (in seconds) for probes following moving feature search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. Error bars show standard errors of the means

Fig. 13 Experiment 3 RTs (in seconds) for probes following static feature search, as a function of display size (x-axis) and probe location (separate lines). Performance for the active group is shown on the left, and performance for the passive group on the right. Error bars show standard errors of the means

Discussion

In Experiment 3, participants searched for a static target, ignoring a set of moving items. The results showed that, in conjunction search, probes were detected more slowly on moving than on static distractors for both passive and active participants. In part, this might reflect masking from moving items (see also Exps. 1 and 2, passive-group data). More importantly, the increase in cost as a function of active search was larger for probes on moving items than for probes on static items (indeed, there was no significant change in cost for probes on static items at the smaller display size; this was only significant at the larger display size). There was some indication that probe costs also increased in the active group for probes on static features (see also Müller et al., 2007), but this effect was similar in magnitude for conjunction and feature search. The data are consistent with inhibitory biases being deployed against all distractors, but this effect was much stronger to distractors with an irrelevant common property (in this case, moving distractors), which would otherwise strongly compete for target selection.

The results of Experiment 3 have important consequences for interpreting the probe effects reported in Experiments 1 and 2. In particular, the data counter the idea that moving items cannot be suppressed because there is a change in their motion properties that cues attention to their locations. Contrary to this theory, there was suppression of probes on moving distractors, and this suppression was greater for participants in the active search group and for conjunction relative to feature search.

The present data also go against the idea that there is always a processing bias favouring moving items (perhaps because they uniquely activate a movement filter). Rather than there being a fixed deployment of attention to certain features, the data suggest that search can be flexibly guided to different features, according to the constraints of the task.

We also note that in contrast to Experiment 2, where there was no suppression of distractors sharing the motion property of targets (i.e., static distractors here), in Experiment 3 there was evidence for some degree of suppression at the higher display size. This is perhaps not surprising, given that prior data had indicated that there can be suppression of distractors differing in form from static targets (Müller et al., 2007). It may be that form suppression has more impact on static than on moving items, perhaps because form is better represented with static stimuli.

One caveat should be raised, however: This concerns the relationship between search efficiency and suppression, as indexed by probe localisation. In Experiments 2 and 3, the magnitude of the suppressive effect on probe localisation was similar (approximately 200 ms), yet search was less efficient for a static than for a moving target. How can this be? If the distractors were equally suppressed in both searches, and if there was no difference in search efficiency for moving and static feature searches, performance should have been equally efficient. Thus, either suppression as indexed by probe localisation is not causal with respect to efficiency (i.e., it is not the mechanism that explains efficient conjunction search) or other factors also contribute to performance that are not measured by probe localisation. We suggest that the latter theory is correct. In the case of search for a static target, top-down suppression of moving distractors may work against a bottom-up bias for attention driven by motion. In contrast, when the target is moving, the top-down bias against static distractors will work in tandem with any bottom-up bias for the moving items, making search more efficient overall.

General discussion

In three experiments, we have documented changes in probe detection in motion–form conjunction search. These effects are a direct consequence of active search processes, rather than any exaggeration of baseline differences in masking, indexed by differences between participants who actively conducted search tasks and responded to probes relative to participants who passively viewed the same displays before responding to the probes. Notably, for participants engaged in active search, there was less efficient detection of probes appearing on distractors that had different movement properties to targets (static distractors in Exps. 1 and 2 and moving distractors in Exp. 3), as compared with distractors that shared the movement properties of the targets (moving distractors in Exps. 1 and 2, and static distractors in Exp. 3). The data are consistent with participants actively suppressing distractors with nontarget motion properties. There was some evidence in Experiment 1 that these suppressive effects tended to be

larger for larger numbers of items on present trials, and in general to be more robust on absent trials.

The results have important consequences for accounts of efficient search for motion–form conjunctions. Firstly, the data show that attentional modulation was applied primarily to one-half of the distractors (either static or moving distractors, depending on the target). Thus, it appears that motion differences are more important than form in guiding search. Had both features of the items been equally important, it should have been difficult to distinguish the RTs to probes on either kind of distractor, due to suppression by motion for one-half of the distractors and suppression by form for the other half. The greater importance of motion than form here is consistent with the subjective experience of searching for motion–form conjunctions and is consistent with a more important role in driving search RTs for distractors sharing target motion than for target form (see von Mühlenen & Müller, 2000). When the task was to detect a static target, there was some evidence for suppression of static distractors differing in form from the target, but this effect was small and restricted only to the larger display size. Thus, while form suppression may play some role in search for static targets (see Müller et al., 2007), it is clearly subsidiary to that of motion differences (when they are present).

Second, the finding of suppressive attentional modulation of distractors is difficult to account for in terms guided search (e.g., Wolfe, 1994), which proposes primarily excitatory guidance. The results also go against an account of search for moving items in terms of a motion filter, since this too predicts no suppression of static distractors under active search conditions for moving targets. The results are also difficult to attribute to a process such as inhibition of return applied serially to each rejected distractor (e.g., Klein, 1988). Inhibition of return is associated with very difficult serial search tasks and is unlikely to be engaged in the case of motion–form conjunctions, given the relatively efficient search performance (at least for Exps. 1 and 2 here). Additionally, Thomas and Lleras (2009) showed that when a difficult search task was segmented by colour and participants were instructed that the target would always appear in one particular colour, probe detection was slower for targets in the cued relevant rather than the uncued irrelevant colour. Thus, in the present tasks, if participants were selecting by motion and searching through the group with the target's motion property, we would expect slower RTs for probes on distractors with this motion property; instead, we found effects based on the motion property of the distractors (not shared with the target).

However, the results are consistent with the idea that inhibitory segregation of irrelevant from relevant sets of items occurs in search, based on a common property distinguishing the items (e.g., Treisman & Sato, 1990).

The results also fit with the idea that search is organised according to the most salient stimulus dimension, and search is then restricted to items with the target feature within that dimension (see Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995). Importantly, the present results indicate that this subset search is achieved not so much by the activation of the subset containing the target (contrary to, e.g., McLeod et al., 1991), but rather by the suppression of the nontarget group (e.g., Treisman & Sato, 1990).

The mechanism of inhibitory segregation examined here may be similar to that found in preview search, in which old items are rejected in parallel by a top-down suppression mechanism (Watson & Humphreys, 1997). It is interesting to note that work on preview search has suggested that this top-down suppression process may take time to develop (Humphreys et al., 2004). This may explain why selective suppression of static objects was weaker with 8 than with 16 items on target-present trials (Exp.1). Note that there would be more time for suppression on absent trials and at larger display sizes. It remains an open question whether the active suppression seen with both motion and temporal preview is specific to cases of spatiotemporal segregation cues, or whether it may generalise more broadly to other cases of relatively efficient conjunction search, including segregation by colour cues. We are currently investigating this possibility.

Importantly, in the present experiments the moving items oscillated in phase, with all items always moving in the same direction. Thus, the moving items not only moved but also created a well-formed perceptual group. McLeod et al. (1991) addressed the significance of grouping by common direction for search efficiency and demonstrated that search remained efficient even if the moving items moved in different directions. Additionally, Pylyshyn (2006) demonstrated inhibition of randomly moving distractors in the context of multiple-object tracking. We predict that distractor suppression in search should generalise to the case in which items move in different directions, although the importance of grouping in this context remains an open question for future research.

The present results add to a growing body of work that has demonstrated the importance of inhibitory processes in visual segmentation (see also Pylyshyn, 2006, and Pylyshyn, Haladjian, King, & Reilly, 2008, for similar results on multiple-object tracking; and Braithwaite et al., 2007; Braithwaite et al., 2005; and Humphreys et al., 2004, for similar results in preview search). The exact relationships between the inhibitory mechanisms at work in these different paradigms remain to be investigated but will be a fruitful area for future research.

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