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Attentional weighting: A possible account of visual field asymmetries in visual search?

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Abstract—Several previous visual search studies measuring reaction times have demonstrated scanning biases across the visual field (i.e. a tendency to begin a serial search in a particular region of space). In the present study, we measured visual discrimination thresholds for a target presented amongst distractors using displays that were short enough to greatly reduce the potential for serial (i.e. scanning) search. For both a motion and orientation task, subjects' performance was significantly better when the target appeared in the inferior, as compared to the superior, visual field (no differences were observed between left and right visual fields). These findings suggest that subjects may divide attention *unevenly* across the visual field when searching for a target amongst distractors, a phenomenon we refer to as 'attentional weighting'. To rule out the possibility that these visual field asymmetries were sensory in nature, thresholds were also measured for conditions in which subjects' attention was directed to the location of the target stimulus, either because it was presented alone in the display or because a spatial cue directed subjects' attention to the location of that target presented amongst distractors. Under these conditions, visual field asymmetries were smaller (or non-existent), suggesting that sensory factors (such as crowding) are unlikely to account for our results. In addition, analyses of set-size effects (obtained by comparing thresholds for a single target *vs*. the target presented amongst distractors) could be accounted for by an unlimited capacity model, suggesting that multiple stimuli can be processed simultaneously without any limitations at an early stage of sensory processing. Taken together, these findings suggest the possible existence of biases in attentional weighting at a late stage of processing. The bias appears to favor the *inferior visual field*, which may arise from the fact that there is more ecologically-relevant information in this region of space.

Keywords: Visual search; attention; visual field asymmetry; motion; orientation; modeling.

INTRODUCTION

Numerous studies have compared performance for visual stimuli/tasks presented in the left visual field (LVF) *vs*. right visual field (RVF), with the assumption that performance reflects the processing capabilities of the right *vs*. left cerebral

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hemispheres, respectively (see Christman and Niebauer, 1997 for a review). There has been relatively less interest in performance differences between the superior visual field (SVF) and inferior visual field (IVF), presumably because these regions of space do not map onto different hemispheres (see Previc, 1990 for a review). Of the studies that have investigated differential SVF *vs*. IVF performance, visual field asymmetries have been reported for various tasks, including reaction time performance (Payne, 1967, IVF advantage), contrast sensitivity (Rijsdijk *et al*., 1980; Lundh *et al*., 1983, IVF advantage at low to moderate spatial frequencies), perceived spatial frequency (Edgar and Smith, 1990, overestimation of spatial frequency in the inferior left quadrant of space), and the perception of illusory contours (Rubin *et al*., 1996, IVF advantage). In the domain of motion processing, an IVF advantage has been demonstrated for direction discrimination (Edwards and Badcock, 1993), centripetal motion processing (Edwards and Badcock, 1993; Raymond, 1994), and motion in depth (Regan, 1986).

In many cases, visual field asymmetries have been attributed to differences in sensory processing (Perry and Cowey, 1985; Connolly and Van Essen, 1984; Van Essen *et al*., 1984; Tootell *et al*., 1988; Virsu and Rovamo, 1979). It has been suggested, however, that spatial attention may vary across the visual field, and thus that asymmetries in visual performance may be driven, in part, by attentional biases across the visual field (e.g. He *et al*., 1996 for motion tasks; but see Carrasco *et al*., 2001 and Cameron *et al*., 2002 for orientation tasks, see Discussion section). In fact, several studies have yielded evidence for visual field asymmetries in *search tasks*, which involve measuring reaction times for the ability to detect the presence or absence of a target presented amongst distractors. Here, reaction times have been found to be faster for targets presented in a particular region of the visual field (e.g. Chaiken *et al*., 1962; Yund *et al*., 1990, see Discussion). These visual field asymmetries are typically attributed to 'scanning biases', i.e. it is presumed that subjects conduct a *serial* search of the items in the display, and that this serial search begins in a particular region of the visual field (see Christman and Niebauer, 1997 for a review). An alternative explanation for visual field asymmetries in search tasks concerns the possibility for differential 'attentional weighting' across the visual field, which we define as a tendency to divide attention *unevenly* across the visual field when searching for a target amongst distractors. In contrast to the scanning bias hypothesis, the attentional weighting hypothesis assumes that processing of multiple items is performed in *parallel* and is unlimited in capacity, but that attentional weighting can differ across items in the display.

In order to investigate the possible existence of attentional weighting, we measured visual discrimination thresholds (rather than reaction times) using displays that were short enough to greatly reduce the potential for serial (i.e. scanning) search. Biases in attentional weighting were assessed by measuring visual field asymmetries under conditions in which the target stimulus was presented amongst confusable distractors, requiring subjects to divide attention across the visual field. In order to determine whether any observed visual field asymmetries under these conditions could be accounted for by *sensory-based* visual field asymmetries, data were also obtained for conditions in which subjects were certain about the target location (and thus directed their attention to it), either because it was presented alone in the display or because a spatial cue alerted subjects to the location of the target presented amongst distractors. The spatial cue condition also allowed us to ask whether biases in attentional weighting could be overridden in displays containing multiple stimuli.

In our first experiment, the same group of subjects was tested on both a motion and orientation discrimination task. We hypothesized that if biases in attentional weighting across the visual field exist, they should generalize across different stimulus conditions (motion *vs*. orientation). In a second experiment, we tested a different group of subjects on the same motion task as in the first experiment, but added a stronger spatial cueing condition. In both Experiments 1 and 2, comparison of performance between conditions in which distractors were present or absent also allowed us to measure set-size effects, as we have performed in earlier studies of motion processing (Dobkins and Bosworth, 2001).

METHODS

Subjects

Subject Group 1 included eleven subjects (8 females, 3 males). Subject Group 2 included eight subjects (6 females, 2 males). One of the eight served as a subject in both groups. All eighteen subjects had normal or corrected-to-normal vision and were naïve to the purpose of the experiment.

Apparatus

Visual stimuli were generated using a SGT Pepper Graphics board (Number Nine Computer Corporation: 640 by 480 pixel resolution, 60 Hz frame rate) residing in a Pentium-based PC, and were displayed on a Nanao F2-21 video monitor (21″ display, 640 × 480 pixels, 60 Hz vertical refresh). A PR-650 SpectraColorimeter (Photoresearch) was used for photometric measurements of our stimuli.

Eye position was monitored using a closed couple device (CCD) infrared camera with variable focus (12.5–75 mm) lens (Model Fc62, Image Sensor), which was focused on the left eye of the subject. The subjects' face was lit with an infrared illuminator and an enlarged image of the eye was viewed by the experimenter on a 12″ Monitor (Ultrak) outside the testing room. Before beginning each block of trials, subjects were instructed to fixate a small green square (0.35°) in the center of the video display, and the outline of the pupil was drawn on transparency film that covered the monitor. Using this set-up, saccadic eye movements could easily be detected, and eye drift within ±2° of fixation could be discerned. Subjects were instructed to maintain fixation throughout the experiment and were informed that the experiment would be temporarily interrupted if eye movements or eye drift were detected. Thus, subjects were highly discouraged from breaking fixation, and the experiment never needed to be interrupted.

Stimuli

Motion stimulus. Motion thresholds were obtained using a *stochastic motion stimulus* (after Williams and Sekuler, 1984; Newsome and Paré, 1988). This stimulus consists of a field of white dots presented within a circular aperture, wherein a proportion of dots (i.e. 'signal' dots) moves in a coherent direction ('rightward' or 'leftward') while the others (i.e. 'noise' dots) move in a random fashion (see Fig. 1A). The signal proportion is varied across trials in order to obtain a *coherent motion threshold* (i.e. the percentage of signal dots required to yield 75% correct directional discrimination). In our display, the motion stimulus consisted of 119 dots (each 0.12° in diameter, area $= 0.011$ degree^2) presented within an 8.0° diameter aperture (dot density $= 1.86$ dots/degree^2). The moving signal dots were displaced 0.35° from one frame to the next, with each frame lasting 50 ms, resulting in a dot speed of 6.9 degrees/s. The trajectory for each moving dot lasted two frames (i.e. 100 ms). The dot then reappeared in a random location within the circular aperture and moved coherently for another two frames, and so on. Noise dots were positioned in a random location from frame to frame. The luminance of all dots was 26 cd/m^2, presented against a black background (0.3 cd/m^2). This high luminance contrast of the dots ensured that the stimulus would not be confusable with the background. In order to obtain motion thresholds, seven different levels of signal were tested, ranging in equal log steps from 2% to 32%. These stimuli were presented in random fashion across trials (method of constant stimuli).

Orientation stimulus. Orientation thresholds were obtained using a stochastic oriented line stimulus, which was designed to be analogous to the stochastic motion stimulus, with the main exception that the oriented line stimulus contained stationary line elements rather than moving dots (see Fig. 1B). Here, a proportion of the line elements were tilted 45° clockwise (CW) or counterclockwise (CCW) from vertical (signal lines) while the remaining lines were oriented vertically (noise lines — see Note 1). Signal strength was varied across trials (between 2 to 90% signal in equal log steps) to obtain an *orientation threshold.* As for the stochastic motion stimulus, the oriented line stimulus consisted of 119 lines (each 0.058 by 0.230° in length, area $= 0.013$ degree^2, 26.2 cd/m^2) presented within an 8.0° diameter aperture (line density $= 1.86$ lines/degree^2). All lines were positioned in a random location on each trial.

Distractors. Distractor stimuli (which were sometimes presented simultaneously with the target stimulus, see below) had all the same properties as the above-described stimuli, yet contained 0% signal. These distractors were highly

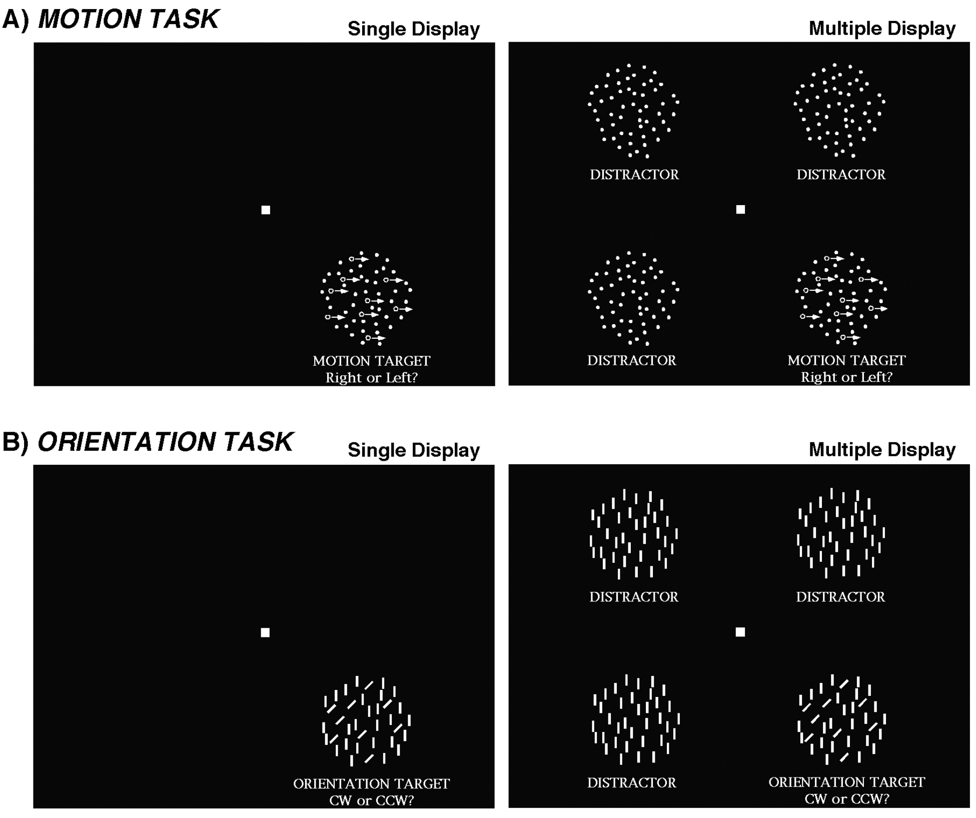

Figure 1. Stimuli and display conditions. For the *motion* task (A), a proportion of dots (i.e. 'signal' dots) moved in a coherent direction ('leftward' or 'rightward') while the others (i.e. 'noise' dots) moved in a random fashion. For the *orientation* task (B), a proportion of line elements (i.e. 'signal' lines) were tilted 45° clockwise (CW) or counterclockwise (CCW) from vertical while the others (i.e. 'noise' lines) were oriented vertically. In both tasks, the signal proportion was varied across trials in order to obtain a *motion or orientation threshold* (i.e. the percentage of signal dots required to yield 75% correct discrimination). Experimental design: The 'target' stimulus, i.e. a stimulus that contained greater than 0% signal, was presented either alone (*left panels*) or simultaneously with three 'distractors', i.e. stimuli that contained 0% signal (*right panels*), in one of four regions of visual space (superior left, superior right, inferior left, inferior right). Subjects were either cued or not cued to the location of the target stimulus (see Methods section for details).

confusable with the target stimulus (i.e. the stimulus containing signal, on which the task was performed), especially when the target stimulus was presented near threshold.

General procedures

Subjects were tested in a darkened room and viewed the video display binocularly from a chin rest situated 57 cm away. Trials containing the motion stimulus and those containing the orientation stimulus were tested in separate blocks. Subjects were instructed to maintain fixation on a small green square (0.35°) in the center of the monitor for the duration of each trial. Subjects initiated each trial with a key press, 50 ms after which the target stimulus (motion or orientation) appeared randomly in one of the four quadrants of visual space (superior left, superior right, inferior left, inferior right), centered 11.3° eccentric to fixation (horizontal and vertical eccentricity = ±8°). Stimulus duration was 200 ms. The purpose of employing this short duration was two-fold. 1) It lessened the likelihood that subjects would attempt to serially search (i.e. scan) the display. 2) Although eye movements were monitored in all subjects (see Apparatus section above), it lessened the likelihood of saccadic eye movements occurring during stimulus presentation. That is, the short duration of the stimulus (200 ms) in comparison with the relatively long latencies for eye movements (~250–300 ms, see He and Kowler, 1989; Saslow, 1967; Schor, 1975) helped to ensure that the stimulus offset occurred before any eye movement could be initiated. Subjects reported perceived direction ('rightward' *vs.* 'leftward') on the motion task or tilt ('CW' *vs.* 'CCW') on the orientation task by pressing one of two appropriate keys (2-AFC). Negative feedback was provided for incorrect trials, which consisted of a white circle (2.3° diameter, 26 cd/m^2) presented 2.3° below the fixation square for 200 ms.

Experimental design

Subject Group 1 was tested in both the motion and orientation tasks, under 4 different conditions, in a 2 (display types) × 2 (spatial cueing conditions) factorial design. The two *display types* were: (1) 'Single Display', the target stimulus was presented alone in one of the four quadrants of visual space (Fig. 1A and 1B, *left columns*). (2) 'Multiple Display', the target stimulus was presented in one visual field quadrant while the three remaining quadrants contained distractors (Fig. 1A and 1B, *right columns*).

The two *pre-cueing conditions* were: (1) 'UnCued', where there was no spatial pre-cue alerting subjects as to which visual quadrant the target stimulus would appear in. Subjects initiated the trial with a key press, and the stimulus appeared 50 ms later. In the Multiple Display, UnCued condition, there was spatial *uncertainty* regarding which stimulus was the target and which were the distractors, since the target and distractors were confusable. Thus, in this condition, subjects had to divide their attention across the visual field to search the display for the target. By contrast, in the Single Display condition, there was spatial certainty about the location of the motion stimulus once it was presented (since all the dots/lines were high-contrast against the background), and thus subjects presumably directed their attention to the relevant location. (2) 'Cued', in which subjects were alerted to the location of the to-be-presented target stimulus with a valid pre-cue, which provided spatial certainty as to the location of the upcoming target. The pre-cue consisted of a 0.23° square (26 cd/m^2) that appeared beforehand in the center of that location (i.e. centered 11.3° eccentric to fixation in one of the four visual field locations). Subjects initiated the trial with a key press, and 50 ms later the pre-cue disappeared and the stimuli were presented. The significance of the pre-cue was explained to subjects, and they were instructed to use the cue to their benefit. Thus, on trials that contained a pre-cue, subjects knew to first direct their visual attention to the appropriate quadrant of visual space before beginning a trial. When the pre-cue was presented in the Multiple Display condition, subjects were informed that the three uncued locations of visual space would contain irrelevant information that should be ignored.

The order of the blocks was randomized and counterbalanced across subjects. The experiment consisted of 7,168 total trials, which comprised 224 trials for each of 4 locations (inferior left, inferior right, superior left, superior right), tested under 4 different conditions: 2 display types (Single *vs*. Multiple) $\times$ 2 cueing conditions (UnCued *vs*. Cued), in 2 different tasks (motion *vs*. orientation). Practice consisted of approximately 1350 trials. Subjects typically required a total of 8–10 hours within one week to complete the experiment.

Rationale. The four conditions described above were employed for the purpose of investigating whether performance asymmetries exist for motion and orientation and to assess whether such asymmetries are due to attentional biases in visual search or are sensory in nature. The *Single Display* condition was designed to investigate the existence of visual field asymmetries that are purely *sensory* in nature. In this condition, there was spatial certainty as to the location of the target stimulus, and thus subjects were expected to direct attention to the relevant location in space. This is true even in the UnCued-Single condition, since there is only one highly visible stimulus in the visual field. The *UnCued-Multiple* condition, in which subjects presumably divided their attention across the visual field, was designed to investigate biases in *attentional weighting*, which we defined as the tendency to divide attention unevenly across the visual field when multiple stimuli are presented simultaneously in a search task. Visual field asymmetries in the UnCued-Multiple Display condition that were over and beyond those observed in the Single Display condition were taken as evidence of a bias in attentional weighting across the visual field. [Note that the present study's version of a 'search' task is somewhat unconventional, in that the target stimulus was always present and subjects had to discern its direction or orientation. Typically, search tasks involve detecting the presence or absence of a target stimulus (e.g. a tilted line) amongst distractors (e.g. vertical lines). Although we could have designed our experiments in this fashion, we preferred to employ a discrimination task because we and others have previously shown this method to yield highly interpretable results for set-size effects in search (Dobkins and Bosworth, 2001; Verghese and Stone, 1995).]

However, differences in visual field asymmetries between the Single Display and UnCued-Multiple Display conditions could still be due to sensory factors, since the two displays were not physically identical. For example, the distractors in the UnCued-Multiple Display may have produced 'crowding', which would not have existed in the Single Display condition. Thus, the purpose of the *Cued-Multiple* Display condition was to equate the stimulus conditions with that of the UnCued-

Multiple Display, yet the spatial pre-cue was meant to direct subjects' attention to the target location. We predicted that, if subjects used this spatial pre-cue efficiently, this manipulation should override visual field asymmetries resulting from biases in attentional weighting (observed in the UnCued-Multiple Display condition). Because cue characteristics such as size and salience differ in their ability to anchor attention to a given region of space (e.g. Cheal and Gregory, 1997), in a second group of subjects, we used a stronger cue, the 'ring-cue' (see below), in order to further test this hypothesis.

The 'Ring-Cue'. Subject Group 2 was tested on the same motion task as Subject Group 1, with the addition of a second cue type — the 'ring-cue', which consisted of a ring that surrounded the target stimulus throughout the duration of the trial. The purpose of this cue type was to provide a strong cue (presumably stronger than the dot pre-cue described above) for anchoring subjects' attention to the target location, specifically when it was presented amongst distractors. The ring consisted of an annulus (inner edge = 11.15°, outer edge = 11.34°, 26 cd/m^2) that appeared around the to-be-presented target location before the start of each trial and remained present throughout the trial. Subjects in this group were tested only on the motion task, with the order of the blocks randomized and counterbalanced across subjects. The experiment consisted of 5376 total trials (896 trials per condition), after practice on approximately 1000 trials. Subjects typically required a total of 4–5 hours within one week to complete the experiment.

Data analysis

Motion and orientation thresholds. Psychometric curves were fit to the data using Weibull functions and maximum likelihood analysis (Weibull, 1951; Watson, 1979). Threshold was defined as the signal level yielding 75% correct performance. Each Weibull function, calculated for each condition and for each of the four visual field locations in which the target stimulus appeared, comprised 224 total trials. In order to investigate superior visual field (SVF)/inferior visual field (IVF) field asymmetries, each subject's thresholds were averaged for *superior right* and *superior left* locations and divided by their averaged threshold for *inferior right* and *inferior left* locations, resulting in a SVF/IVF threshold ratio. Likewise, to investigate right visual field (RVF)/left visual field (LVF) asymmetries, each subject's averaged threshold for *superior right* and *inferior right* locations were divided by their averaged threshold for *superior left* and *inferior left* locations, resulting in a RVF/LVF threshold ratio. This was performed separately for the motion and orientation tasks.

In order to compare performance between conditions, threshold ratios were averaged across subjects. Note that, as in our previous experiments on motion processing (Dobkins and Bosworth, 2001), mean thresholds did not differ significantly for Cued-Single *vs*. UnCued-Single conditions (data from Subject Group 1-motion task: $p = 0.15$, 2-tailed t-test; orientation task: $p = 0.47$, 2-tailed t-test) and thus data for these conditions were combined. Further supporting the collapsing of data for the UnCued-Single and Cued-Single conditions, an analysis of slopes of the psychometric functions also revealed no significant difference between mean slopes for the two (data from Subject Group 1-motion task: $p = 0.99$, 2-tailed t-test; orientation task: $p = 0.33$, 2-tailed t-test). Also, because sensitivity data are known to conform to normal distributions when log-transformed (Gunther and Dobkins, 2002), all statistical analyses and averages were performed on log threshold values. Pairwise comparisons (t-tests) were made between different conditions, selected *a priori* based on the reasoning explained in the Rationale segment of the Methods section above. The t-tests were 2-tailed when we had no prediction about the direction of the effect, and 1-tailed when we did.

RESULTS

Visual field asymmetries for motion

Group mean threshold ratios and standard errors obtained from the eleven subjects in Group 1 are shown for the *motion task* in Fig. 2. (Mean threshold data from this subject group are presented in Table 1, separately for the motion and orientation

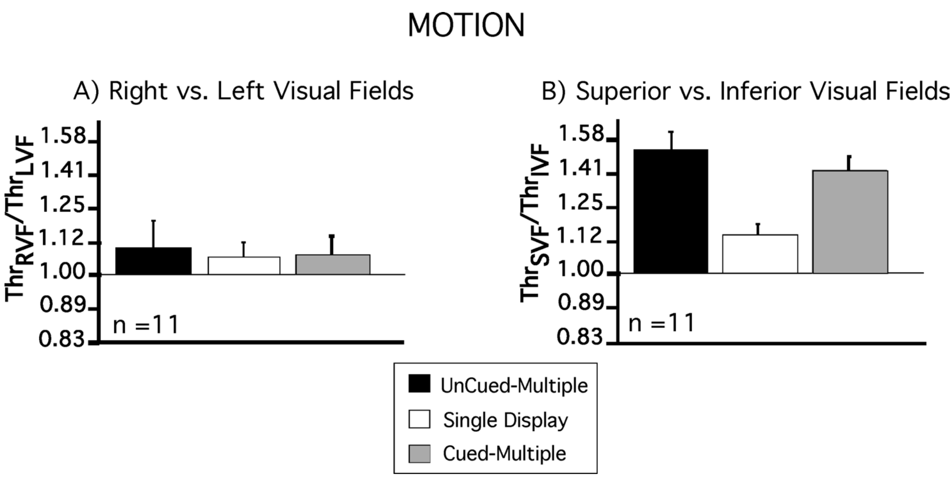

Figure 2. Visual field asymmetries for motion: Subject Group #1. Group mean threshold ratios and standard errors are shown for the UnCued-Multiple (*black bars*), Single Display (*white bars*) and Cued-Multiple (*grey bars*) conditions. *Left Panel*: Right visual field (RVF) *vs.* left visual field (LVF) threshold ratios (Thr_{RVF}:Thr_{LVF}) reveal no significant right *vs.* left asymmetries across the visual field for motion. *Right Panel*: Superior visual field (SVF) *vs.* Inferior visual field (IVF) threshold ratios (Thr_{SVF}:Thr_{IVF}) reveal a strong IVF advantage under conditions in which subjects presumably divided attention across the visual field (i.e. UnCued-Multiple), and a smaller IVF advantage under conditions in which subjects directed attention to the relevant location in space (i.e. Single Display). The difference between these two conditions is assumed to reflect a bias in attentional weighting in favor of the inferior visual field. The use of a dot pre-cue (Cued-Multiple) reduced this bias slightly. See text for details and statistics.

Table 1.
Mean threshold data (geometric means) for Group #1 for the motion and orientation tasks

	Single-display								Multiple-display							
	UnCued				Cued				UnCued				Cued			
	IL	IR	SL	SR	IL	IR	SL	SR	IL	IR	SL	SR	IL	IR	SL	SR
Motion	6.6	6.9	7.3	8.4	6.0	6.8	7.4	6.8	9.4	12	17	16	5.0	5.9	7.8	7.6
Orientation	15	16	16	16	13	18	15	16	24	30	33	39	14	16	16	20

tasks.) Right visual field (RVF)/Left Visual Field (LVF) threshold ratios are presented in the *left* panel of Fig. 2. RVF/LVF ratios greater than 1.0 indicate a LVF advantage. For all three conditions (*UnCued-Multiple, black bar, Single Display, white bar and Cued-Multiple, grey bar*), threshold ratios did not differ significantly from 1.0 ($p > 0.07$, 2-tailed t-test), indicating neither sensory-based nor attentionally-based biases across the LVF *vs*. RVF. Note that this finding is generally in line with previous results reporting very small or inconsistent differences between RVF and LVF for motion processing (see Christman and Niebauer, 1997 for a review).

SVF/IVF threshold ratios are presented in the *right panel* of Fig. 2. SVF/IVF ratios greater than 1.0 indicate an IVF advantage. In the UnCued-Multiple Display condition (*black bar*), where spatial uncertainty about the target location presumably resulted in subjects dividing their attention across the visual field, there was a 1.53-fold IVF advantage that was significantly greater than 1.0 ($p < 0.0001$, 2-tailed t-test). A significant IVF advantage was also observed in the Single Display condition (*white bar*, mean SVF/IVF ratio = 1.14-fold, $p < 0.01$, 2-tailed t-test), where spatial certainty allowed subjects to direct attention to the target location. In line with previous suggestions (Virsu and Rovamo, 1979; Connolly and Van Essen, 1984; Van Essen *et al*., 1984; Perry and Cowey, 1985; Tootell *et al*., 1988), this latter result suggests a small but significant *sensory* IVF advantage for motion processing. Most importantly, the IVF advantage was significantly larger under conditions of divided *vs*. directed attention, as evidenced by SVF/IVF ratios that were significantly larger in the UnCued-Multiple, than in the Single Display, condition ($p < 0.01$, 2-tailed t-test). This difference between conditions is consistent with the attentional weighting hypothesis, that is, subjects appear to divide attention *unevenly* across the visual field, with a bias towards the IVF, when searching for a target presented amongst distractors.

However, it is still possible that differences in visual field asymmetries between the Single Display and UnCued-Multiple Display conditions could be due to sensory, rather than attentional, factors, since the two displays were not physically identical. To address this, we also tested subjects with the Cued-Multiple Display. Here, the stimulus conditions were identical to those of the UnCued-Multiple condition, yet the appearance of a pre-cue was meant to direct subjects' attention to the location of the target presented amongst distractors. If the large IVF advantage seen in the UnCued-Multiple condition is due to biases in attentional weighting across the visual field, we predicted that this advantage would be diminished in the Cued-Multiple Display. In fact, the mean SVF/IVF threshold ratio in this condition (*grey bar*, mean SVF/IVF ratio = 1.43-fold) was reduced as compared to the UnCued-Multiple condition, although not significantly so ($p = 0.24$, 1-tailed t-test). In addition, SVF/IVF threshold ratios for the Cued-Multiple condition were significantly greater than 1.0 ($p < 0.0001$, 2-tailed t-test), and significantly greater than those observed in the Single Display condition ($p < 0.05$, 2-tailed t-test). There are two possible explanations for why the IVF advantage was stronger in both the Cued-Multiple and UnCued-Multiple conditions as compared to the Single Display condition, one sensory, the other attentional, in nature. The sensory explanation proposes that the difference is due to the addition of distractor stimuli in the Multiple Display conditions, which differentially affect the processing of motion stimuli in the IVF *vs*. SVF. This could be a result of differential effects of 'crowding' in the SVF *vs*. IVF, an issue we return to in the Discussion section. The attentional explanation proposes that the pre-cue (which consisted of a small 0.23° dot appearing beforehand in the location of the to-be-presented target stimulus) was simply not strong enough to anchor subjects' attention to the relevant target location and thereby override attentional weighting biases across the visual field.

To distinguish between these alternative explanations for results obtained in the Cued-Multiple condition, we tested a second group of subjects with two different cue types; the same dot pre-cue as was employed for Subject Group 1 and, in addition, a more potent ring-cue (see *Methods*). Data for this separate group of eight subjects (who were run only on the motion task) are shown in Fig. 3 (with mean geometric thresholds presented in Table 2). The results from this second group were nearly identical to those observed for Subject Group 1, there were significant differences between SVF and IVF threshold data. Specifically, in the UnCued-Multiple condition (*black bar*), a significant 1.41-fold IVF advantage was observed ($p = 0.02$, 1-tailed t-test — see Note 2). In the Single Display condition (*white bar*), data were combined across the *UnCued-Single*, *Dot-Cued-Single*, and *Ring-Cued-Single* conditions because there were no differences between the three (see *Data Analysis in Methods*). Here there was a small, 1.15-fold IVF advantage, which was only marginally significant ($p = 0.06$, 1-tailed t-test). In line with the attentional weighting hypothesis, the IVF advantage was significantly greater in the UnCued-Multiple condition than in the Single Display condition ($p = 0.025$, 1-tailed t-test). As for Subject Group 1, the use of a dot pre-cue in the Cued-Multiple Display condition (*grey bar*) did not significantly reduce the IVF advantage compared to the UnCued-Multiple condition ($p = 0.19$, 1-tailed t-test). Here, the mean SVF/IVF ratio was 1.28-fold, which was significantly greater than 1.0 ($p = 0.013$, 1-tailed t-test). Also, like Subject Group 1, there was no significant difference in RVF and LVF threshold ratios observed for any condition ($p > 0.06$ for all conditions, 2-tailed t-test), and thus these data are not shown.

Most importantly, as predicted, in the Ring-Cued-Multiple condition (Fig. 3, *hatched bar*) SVF/IVF threshold ratios (mean = 1.12) were reduced compared to the UnCued-Multiple condition, although this effect was only marginally significant ($p = 0.07$, 1-tailed t-test). However, note that the SVF/IVF ratios in the Ring-Cued-Multiple condition were indistinguishable from those observed in the Single Display condition ($p = 0.38$, 1-tailed t-test). Thus, in general, the more salient ring-cue substantially diminished the IVF attentional bias, presumably by anchoring subjects' attention to the relevant target location in visual space. Furthermore, these results obtained with the ring-cue suggest that the significant IVF advantage observed for the Cued-Multiple condition employing a small dot pre-cue (for both Subject Groups 1 and 2) might have been driven by biases in attentional weighting

Table 2.
Mean motion task threshold data (geometric means) for Group #2

	Motion											
	UnCued				Cued (Dot)				Ring-Cued			
	IL	IR	SL	SR	IL	IR	SL	SR	IL	IR	SL	SR
Single	11	9.0	12	10	9.3	8.1	11	9.1	8.1	8.2	11	8.4
Multiple	16	12	22	17	7.8	7.0	12	8.1	9.1	7.4	10	8.5

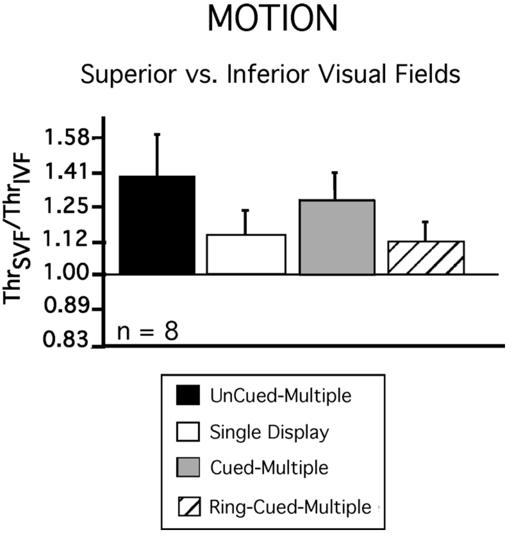

Figure 3. Visual field asymmetries for motion: Subject Group #2. Group mean threshold ratios and standard errors for the UnCued-Multiple (*black bar*), Single Display (*white bar*) and Cued-Multiple (*grey bar*) conditions replicate those obtained for subject group #1 (see Fig. 2). This subject group was tested with an additional condition, 'Ring-Cued-Multiple' (*hatched bar*), which directed subjects' attention to the location of the target presented amongst distractors. The use of this stronger ring-cue nearly eliminated the inferior visual field bias. See text for details and statistics.

that overrode the spatial certainty afforded by that cue (but see the Discussion section for an alternative possibility based on crowding effects).

In sum, the results from these experiments suggest a small sensory bias for motion processing in the IVF, as well as a relatively large attentional weighting bias in the IVF. Moreover, the results from our ring-cue condition suggest that this attentional bias can be overridden to the extent that a sufficient anchoring cue is provided. In order to determine whether this bias is specific to the particular stimulus/task employed, we also tested Subject Group 1 on an orientation discrimination task, the results for which are presented below.

Visual field asymmetries for orientation

Group mean threshold ratios and standard errors obtained from Subject Group 1 are shown for the *orientation task* in Fig. 4. As for motion data in Figs 2 and 3, ratios for orientation are presented for the UnCued-Multiple (*black bars*), Single Display (*white bars*), Cued-Multiple (*grey bars*) conditions. RVF/LVF threshold ratios are presented in the *left panel* of Fig. 4. Although RVF/LVF threshold ratios were not significantly greater than 1.0 for any of the three conditions ($p > 0.07$ for all conditions, 2-tailed t-test), there did appear to be a tendency towards a LVF advantage. However, there were no significant differences in RVF/LVF ratio

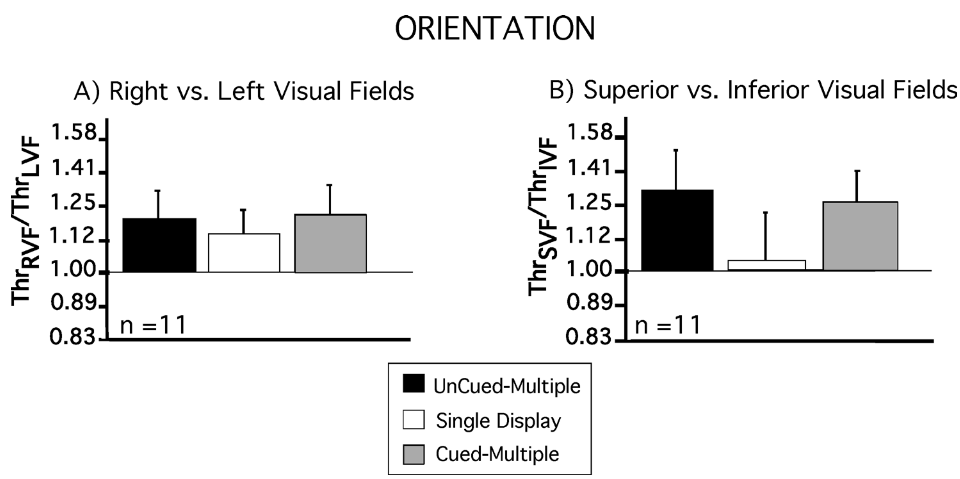

Figure 4. Visual field asymmetries for orientation: Subject Group #1. Group mean threshold ratios and standard errors are shown for the UnCued-Multiple (*black bars*), Single Display (*white bars*) and Cued-Multiple (*grey bars*) conditions. *Left Panel*: Right visual field (RVF) *vs*. Left visual field (LVF) threshold ratios (Thr_{RVF}:Thr_{LVF}) reveal a trend for a left visual field advantage, which is sensory in nature (see text for details). *Right Panel*: Superior visual field (SVF) *vs*. inferior visual field (IVF) threshold ratios (Thr_{SVF}:Thr_{IVF}) reveal an IVF advantage in the UnCued-Multiple condition, and a non-significant IVF advantage in the Single Display condition. Thus, in line with our conclusions from the motion task, these data suggest that, when searching for a target amongst distractors, attention is weighted towards the inferior visual field. Also, as was the case in the motion task, the use of a dot pre-cue (Cued-Multiple) reduced this bias only slightly. See text for details and statistics.

between the Single Display and UnCued-Multiple conditions ($p = 0.51$). Thus, as for data obtained on the motion task (see above), this results suggests a lack of biases in attentional weighting across the RVF *vs*. LVF.

SVF/IVF threshold ratios are presented in the *right panel* of Fig. 4. Similar to the motion task, a large and significant IVF advantage was observed in the UnCued-Multiple Display condition (mean threshold ratio = 1.33, $p < 0.05$, 1-tailed t-test, see Note 3). In contrast to the motion task, however, SVF/IVF ratios in the Single Display condition were not significantly different from 1.0 (mean threshold ratio = 1.04, $p = 0.42$, 1-tailed t-test), indicating no clear sensory IVF *vs*. SVF asymmetry for orientation discrimination. SVF/IVF threshold ratios were larger in the UnCued-Multiple than in the Single Display condition. Although this effect was only marginally significant ($p = 0.09$, 1-tailed t-test), in line with our conclusions from the motion task, this result for the orientation task is suggestive of attentional weighting, that is, subjects may divide attention *unevenly* across the visual field, with a bias towards the IVF, when searching for a target presented amongst distractors.

Of course, this suggestion would be stronger if, for the orientation task, we had also obtained data for the Multiple-Display Ring-Cued condition and found IVF/SVF ratios comparable to those observed in the Single Display condition (as observed for the motion task in Subject Group 2). And note that, similar to the results from the motion task, the use of dot pre-cue in the Multiple condition did not substantially diminish the IVF advantage, i.e. SVF/IVF ratios for Cued-Multiple (mean threshold ratio = 1.21) and UnCued-Multiple did not differ significantly ($p = 0.59$, 2-tailed t-test).

Set-size effects

The data from these experiments also allow us to investigate the effects of set-size, as we have performed previously for a motion task (Dobkins and Bosworth, 2001). Specifically, we compared thresholds in the UnCued-Multiple condition with those from the UnCued-Single Display condition. The Single Display condition is equivalent to a set-size of 1, while the UnCued-Multiple condition is equivalent to a set-size of 4 (i.e. one ‘target’ stimulus containing motion presented simultaneously with three ‘distractor’ stimuli). For each subject, a *set-size effect* was obtained by dividing the threshold for set-size 4 by the threshold for set-size 1 (i.e. $\mathrm{Thr}_{\text{set-size }4}/\mathrm{Thr}_{\text{set-size }1}$), separately for the motion and orientation tasks, and separately for SVF and IVF data (motion data for both groups of subjects were combined, total number of subjects = 18).

Mean set-size effects and standard errors for the motion task (*grey bars*) and orientation task (*white bars*) are plotted in Fig. 5, separately for the SVF and IVF. For the *motion* task, set-size effects were 1.94 for the SVF and 1.51 for the IVF, both of which were significantly greater than 1.0 ($p < 0.00005$ 1-tailed t-test and $p < 0.0005$, 1-tailed t-test, respectively). On average, the set-size effect for the motion task was 1.71 ($p < 0.00005$, 1-tailed t-test). For the *orientation*

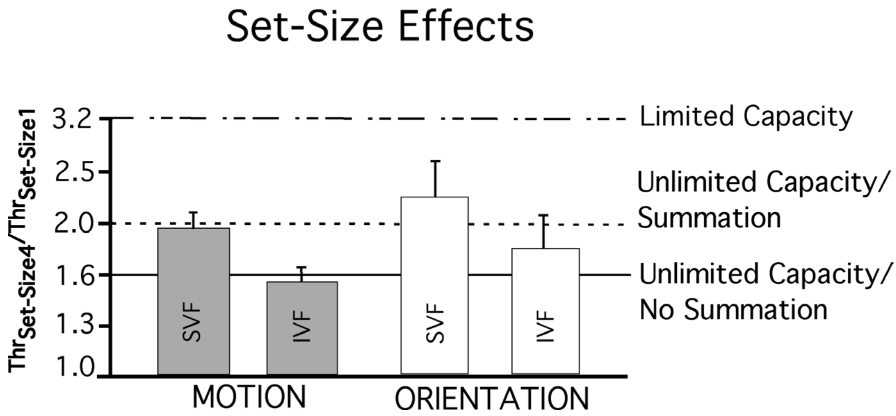

Figure 5. Set-size effects. Group mean threshold ratios ($\mathrm{Thr}_{\text{set-size 4}}/\mathrm{Thr}_{\text{set-size 1}}$) and standard errors are plotted for the motion task (*grey bars*) and orientation task (*white bars*), separately for the SVF and IVF. Threshold ratios are greater than 1.0, indicating better performance in the set-size 1 condition. For *motion* data, Inferior Visual Field (IVF) threshold ratios are statistically closest to the predictions for 'Unlimited Capacity/No Summation' (*solid line*) and Superior Visual Field (SVF) threshold ratios are closest to 'Unlimited Capacity/Summation' (*dashed line*), and neither is consistent with the predictions of the 'Limited Capacity' model (*dotted-dashed line*). For *orientation* data, IVF threshold ratios are consistent with either 'Unlimited Capacity/No Summation' or 'Unlimited Capacity/Summation', SVF threshold ratios are closest to the predictions for the 'Unlimited Capacity/Summation', and neither is consistent with the predictions of the 'Limited Capacity' model. See text for details.

task, set-size effects were 2.20 for the SVF and 1.76 for the IVF, both of which were significantly greater than 1.0 ($p < 0.00005$ 1-tailed t-test). On average, the set-size effect for the orientation task was 1.97 ($p < 0.00003$, 1-tailed t-test). These set-size effects indicate that performance on the motion and orientation tasks suffers in the face of spatial uncertainty regarding the location of a target. Two opposing models have been put forth to explain the impairment in performance that results from increasing set-size. *Unlimited capacity models* posit that the quality of sensory processing is maintained as the number of items in a visual display increases. However, visual performance is worse for larger, as compared to smaller, set-sizes due to the increased probability for errors occurring at the *decision level*. By contrast, *limited capacity models* postulate that set-size effects occur because increasing the number of visual stimuli to be attended necessarily degrades the quality of processing for each.

As described in detail previously (e.g. Mulligan and Shaw, 1980; Shaw, 1980, 1982, 1984; Graham *et al*., 1987; Palmer *et al*., 1993, 2000; Palmer, 1994, 1995; Verghese and Nakayama, 1994; Verghese and Stone, 1995), these two models yield quantitatively distinct predictions for the effects of set-size on visual thresholds. The theories and equations behind these models, which are based on Signal Detection Theory, are described in detail elsewhere (Dobkins and Bosworth, 2001). In brief, in the case of direction discrimination, these models assume that an observer's directional decisions ('leftward' or 'rightward') are based on the directional detector (leftward or rightward detector) with the *maximal* response. When there is unlimited capacity, the activity in these detectors is unaffected by increasing set-size, yet performance is expected to decline because the presence of noise distractors increases the overall probability of decision errors. Specifically, the unlimited capacity maximum rule model predicts that thresholds should be 1.60 × higher for set-size 4, as compared to set-size 1 ($\mathrm{Thr}_{\text{set-size }4}/\mathrm{Thr}_{\text{set-size }1} = 1.60$). Alternatively, a slight variation of the unlimited capacity maximum rule supposes that the activities across detectors with the same direction preferences are summed together before the maximum rule decision is made. This unlimited capacity model, referred to as the 'summation rule', predicts a slightly higher threshold ratio of 2.0. The *limited capacity* model also assumes that a maximum rule decision is employed. However, owing to attentional resources needing to be divided amongst the number of visual stimuli presented, the variance of activity in each detector rises proportionally with increasing set-size. Here, the predicted threshold ratio is 3.20.

Predicted threshold ratios for the different models of attention are presented along with the data in Fig. 5: Unlimited Capacity/*No Summation* (solid line), Unlimited Capacity/*Summation* (dashed line) and *Limited Capacity* (dotted-dashed line). For the *motion* task, statistical analyses reveal that set-size effects were significantly different from the prediction for Limited Capacity, in both the SVF ($p < 0.001$, 2-tailed t-test) and IVF ($p < 0.001$, 2-tailed t-test), indicating that this model cannot adequately account for the data. However, which Unlimited Capacity model provided a better fit to the data differed for the SVF and IVF. For the IVF data, set-size effects were consistent with Unlimited Capacity/*No Summation* ($p = 0.38$, 2-tailed t-test) and not Unlimited Capacity/*Summation* ($p = 0.001$, 2-tailed t-test). Such findings corroborate previous results from studies of set-size effects for motion processing (Verghese and Stone, 1995; Dobkins and Bosworth, 2001). Conversely, SVF set-size effects were consistent with Unlimited Capacity/*Summation* ($p = 0.65$, 2-tailed t-test) and not Unlimited Capacity/*No Summation* ($p = 0.008$, 2-tailed t-test).

For the *orientation* task, set-size effects were significantly different from that predicted by the Limited Capacity model, in both the SVF ($p = 0.05$, 2-tailed t-test) and IVF ($p = 0.002$, 2-tailed t-test), indicating that this model cannot account for the data. And, like the case for motion data, set-size effects for the orientation task in the SVF were closer to the Unlimited Capacity/*Summation* prediction ($p = 0.56$, 2-tailed t-test), than to the Unlimited Capacity/*No Summation* prediction ($p = 0.08$, 2-tailed t-test). For the IVF, set-size effects were consistent with either Unlimited Capacity model (Maximum Rule: $p = 0.54$, 2-tailed t-test; Summation Rule: $p = 0.41$, 2-tailed t-test). These set-size effects for orientation discrimination are generally in line with those reported previously by others (Pavel *et al.*, 1992; Palmer *et al.*, 1993; Palmer, 1994; Baldassi and Verghese, 2002).

In sum, in line with results from previous studies investigating set-size effects for various aspects of visual processing (see Palmer, 1993), data from the motion and orientation tasks of the present study support unlimited capacity for processing multiple stimuli simultaneously. The only difference between set-size effects for the SVF and IVF observed in our study was a tendency for stimulus responses to be summed before a maximum rule is computed (and this tendency was also greater in the orientation, as compared to the motion, task).

DISCUSSION

The results of these experiments suggest that search for a motion or orientation target amongst distractors is performed in parallel, with attention being more heavily weighted in the inferior visual field. The results also suggest that this attentional weighting can be overridden when a sufficiently strong cue directs subjects' attention to the location of the target. These findings and their interpretations are discussed in several contexts. First, we discuss our results with respect to previous studies investigating the effects of attention in different regions of the visual field. Second, we discuss whether the IVF advantage observed in our study might instead be attributable to scanning biases (like those previously reported in the literature) or differential crowding effects across the visual field. Third, we address whether the attentional bias observed in our experiments reflects changes at an early stage in sensory processing *vs.* at a later decision-level stage.

Relation to previous studies

A recent study by Carrasco *et al*. (2001) also investigated differential effects of attention across the visual field. The main point of their study was to determine whether percent correct performance on an orientation discrimination task differed when the location of a target stimulus (presented either alone or amongst a variable number of distractors) was cued *vs*. uncued, and whether cueing effects varied depending on the location of the target stimulus. The data in their study most relevant to the present study is the comparison of their 'performance fields' (i.e. the shape depicted by percent correct performance at particular locations in the visual field) obtained for the condition in which the target location was *un*cued and was presented amongst three distractors (akin to our *UnCued-Multiple condition*) and those obtained for the condition in which a single target stimulus was presented (akin to our *Single Display condition*). Performance fields appeared very similar between these two conditions. This result, which suggests a lack of attentional bias across the visual field, is contradictory to those of the present study.

There are at least four potential explanations for the differences observed between the Carrasco *et al*. and the present study. First, orientation tasks that use stationary stimuli (as employed by Carrasco *et al*.) may yield weaker attentional biases than do motion stimuli/tasks, and thus this effect may not have been revealed in the Carrasco *et al*. study. There is some credence to this possibility given that, in the present study, the attentional bias appeared somewhat weaker in the (stationary) orientation task, as compared to the motion task (see Figs 2 and 4). Second, the Carrasco *et al*. study used *percent correct* performance, whereas the present study employed *threshold* values. Carrasco *et al*.'s comparison of performance fields between conditions is complicated by the fact that the relationship between differences in percent correct and differences in *detectability* varies with percent correct (i.e. the difference between 95% and 85% correct performance is not equivalent to the difference between 75% and 65% correct performance). However, a more recent analysis of their data using d' (which better reflects detectability) yielded nearly identical results to their analyses using percent correct (L. Cameron, personal communication), and thus this factor is unlikely to account for the differences across studies. Third, Carrasco *et al*. used transient spatial pre-cues, which are thought to invoke automatic attentional processes. This is in contrast to the sustained pre-cue used in the present study, which is thought to invoke more volitional attentional processes (Nakayama and Mackeben, 1989). Thus, differences between studies can be reconciled by proposing that there exist biases in volitional, but not automatic, attention across the visual field. Results from a study of contrast sensitivity for an orientation task (Cameron *et al*., 2002), which used similar transient automatic attention pre-cues, also found no difference in attentional effects across the visual field using this type of cue. Last, Carrasco *et al*.'s stimulus duration (40–67 ms) was clearly short enough to preclude a serial search, whereas our stimulus duration was significantly longer (200 ms), which could possibly have allowed subjects to serially search the display, an issue we address below.

Scanning biases

In the present study, we used a relatively short (200 ms) stimulus duration, the purpose of which was to reduce the potential for serial search. Had subjects attempted to scan the display serially, our finding of an IVF advantage in the UnCued-Multiple condition could reflect a 'scanning bias'; that is, subjects might have began a serial search consistently in the inferior regions of space. There are several reasons why we believe that a scanning bias is unlikely to account for our results. First, several previous studies have attempted to measure the time it takes to redirect attention from one location to another, with estimates varying from 50–150 ms, depending on the task (e.g. Tsal, 1983; Eriksen and Yeh, 1985; Krose and Julesz, 1989). These values, together with the time it takes to optimally process each stimulus ($\sim$200 ms, see Dobkins and Bosworth, 2001), would make a serial search highly inefficient, and thus we strongly suspect that subjects would not adopt this strategy. Second, although subjects could potentially have assumed a strategy of directing their attention to a *single* region of space on the majority of trials (which, in theory, could result in an IVF advantage), this would predict psychometric functions that asymptote far below 100% correct performance (e.g. Davis *et al*., 1983), which was never observed in our psychometric functions. For this reason, this account of our results is highly unlikely.

Perhaps most importantly, previous experiments that have measured reaction times for detecting the presence of a suprathreshold target presented amongst distractors, a task that presumably invokes a *serial* search, typically report scanning biases in the superior (and right) visual field (e.g. Chaiken *et al*., 1962; Yund *et al*., 1990). Because this bias does not favor the IVF, we feel confident that the IVF advantage observed in the present experiment is not due to serial scanning biases.

Crowding effects

Here we address the possibility that greater effects of crowding in the SVF could have contributed to our results. Crowding refers to the decreased ability to identify a target stimulus when it is flanked by other stimuli *vs*. presented alone. Although crowding has, by some, been attributed to sensory factors like lateral masking (e.g. Flom *et al*., 1963; Wolford and Chambers, 1984; but compare Pelli *et al*., 2003), more recently, crowding effects have also been attributed to *attentional* limitations, including processing capacity/attentional resources (Wolford and Chambers, 1984; Parkes *et al*., 2001), attention orienting (Strasburger *et al*., 1991), uncertainty (Leat *et al*., 1999), the size of an attentional window (Bahcall and Kowler, 1999), and attentional resolution (He *et al*., 1996, 1997).

There are several reasons why we believe that differential crowding between the IVF and SVF is unlikely to account for our results, whether the crowding be sensory or attentional in nature. First, the stimuli in our Multiple Display conditions were placed sufficiently apart such that crowding effects should have been minimal (but see Bouma, 1970 and Pelli *et al*., 2003 for evidence that crowding can occur for letter stimuli that are separated by a distance of half the viewing eccentricity or less). Second, the fact that spatial cueing the location of the target presented amongst distractors acted to diminish the IVF advantage, particularly when the *ring cue* was employed, suggests that crowding alone cannot account for our results. In fact, if crowding were greater in the SVF, we might have expected that the ring cue, which surrounded and thus crowded the target, would have exacerbated the SVF disadvantage. (Note, of course, that riding on top of this crowding effect, the ring cue will also, by providing spatial certainty about target location, improve performance overall.) Since this prediction is in the direction opposite to that observed (i.e. the ring cue was found to diminish the SVF disadvantage), we find it unlikely that differential crowding in the SVF *vs*. IVF accounts for our results.

Still, we cannot rule out potential crowding effects. For example, one might propose that the ring cue served to *diminish* the effects of crowding by helping to segment the visual scene (see Pelli *et al*., 2003 for a current review of the relationship between crowding and feature integration, object recognition, etc.). In this case, the diminished SVF disadvantage observed with the ring cue could possibly be attributed to selective *lessening* of crowding effects in the SVF. Further research will be needed to investigate this possibility.

Attentional weighting bias: early sensory or decision-based?

Given that our results reflect an attentional weighting bias across the visual field, we address whether this bias is more likely to reflect changes in early sensory processing or changes at a later decision-level stage. We address this question by, first, discussing the results from the present and previous studies' analyses of set-size effects. Second, we discuss the results of modeling studies, which account for attentional weighting biases by processes at the decision level.

In the present study, we analyzed set-size effects by comparing thresholds for the UnCued-Multiple Display condition with those for the UnCued-Single Display condition (see *Results*). The results of these analyses revealed that set-size effects for motion and orientation can be modeled by a simple decision rule based on signal detection theory (see Fig. 5). According to this model, the quality of sensory processing is maintained as the number of items in the display increases, however, performance declines because the presence of distractors increases the number of errors occurring at the decision level. Thus, contrary to early notions, which proposed that dividing attention across multiple stimuli limits the processing for each (e.g. Broadbent, 1958; Treisman and Gelade, 1980), our results add to the mounting evidence for *unlimited* capacity in visual attention.

Like the results of the present study, many previous psychophysical studies employing threshold techniques have been able to quantitatively account for set-size effects assuming an *unlimited*, as opposed to a *limited* capacity model. This has been shown in a variety of visual tasks such as direction and speed discrimination (Verghese and Stone, 1995; Dobkins and Bosworth, 2001), orientation discrimination (Pavel *et al.*, 1992; Palmer *et al.*, 1993; Palmer, 1994; Baldassi and Verghese, 2002, but see Morgan *et al.*, 1998; Verghese and Nakayama, 1994), luminance discrimination (Cohn and Lasley, 1974; Lasley and Cohn, 1981; Shaw, 1984; Palmer, 1994), color discrimination (Palmer, 1994; Verghese and Nakayama, 1994; Monnier and Nagy, 2001), size and length discrimination (Palmer, 1994), letter discrimination (Bennett and Jaye, 1995; McLean *et al.*, 1997; but see Shaw *et al.*, 1983 and Shaw, 1984 for different results when the task is letter *localization*), as well as contrast detection (Davis *et al.*, 1983 and see Carrasco *et al.*, 2000). In sum, the consensus across studies is that multiple stimuli can be processed in parallel without any loss in the quality of stimulus processing at an early sensory level. For this reason, we argue that the attentional biases we observed need not affect early sensory processing, but rather, are likely to be explained by the weighting of responses at the decision level.

Most of the aforementioned studies employed unlimited capacity (decision-based) models for set-size effects that assume *equal* weighting across stimulus locations, however, others have considered models that allow for unequal weighting, and this weighting is assumed to occur at a late stage of processing (Kinchla, 1977; Kinchla and Collyer, 1974). In addition to applying attentional weighting models to set-size effect data, others have successfully used such models to account for attentional *cueing* effects. Here, cueing effects are well modeled by a Bayesian sum of weighted likelihoods model but not by a Limited Capacity model (Shimozaki *et al.*, 2003, and see Eckstein *et al.*, 2002 for further evidence that attentional cueing does not necessarily affect early, sensory processing of stimuli in a classification image paradigm). The weighting of inputs at a late stage of processing has also been shown to adequately account for data in a recent feature-based attention study. Murray *et al.* (2003) conducted several experiments in which subjects directed attention to parts of a stimulus based on contrast polarity (white or black) while performing global direction of motion and global orientation discrimination tasks. Using a Bayesian model, they showed that their data could be explained by assuming that subjects ascribe different attentional weights to information from different parts of a stimulus. Their linear cue-combination framework model involved attentional weighting of the relative weight that subjects assign to the internal responses to target and distractor stimuli. The model involved attentional weighting only at the *decision stage of processing*, and did not involve any change in the quality of underlying, internal stimulus representations with attentional weighting. This model could feasibly be extended to account for the IVF bias observed in our experiment. Here, the information supplied to the model would simply consist of responses to target and distractor stimuli presented in *different* parts of space, rather than responses to target and distractor features of a single stimulus at one location in space (see Kinchla, 1977 for similar notions about subject responses in visual search reflecting a weighted sum of decision variables that represented possible target locations).

CONCLUSIONS

In sum, the present study demonstrates an inferior visual field advantage in performance when subjects search for a target amongst distractors. We attribute this phenomenon to a tendency to divide attention *unevenly* across the visual field when searching for a target amongst distractors, which we refer to as a bias in ‘attentional weighting’. This effect generalizes across two different visual tasks and appears to be attentional, rather than sensory, in nature since inferior visual field advantages were smaller or insignificant under conditions in which subjects’ attention was directed to the location of a target stimulus presented alone. This bias in attentional weighting, which favors the inferior visual field, may arise from the fact that there is more ecologically-relevant information (e.g. optic flow) in this region of space (Previc, 1990).

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NOTES

1. Note that the 'noise' lines were not noisy in the sense of being presented at a random orientation. Instead, the presence of vertical lines provided noise by adding irrelevant orientation information to the display. We chose this method because pilot experiments suggested that presenting randomly-oriented lines would have made the orientation task much too difficult in comparison to the motion task.
2. Note that, for Subject Group 2, we used 1-tailed t-tests for the SVF/IVF data since we had a clear prediction about the direction of the effect based on data from Subject Group 1.
3. For SVF/IVF data obtained in the orientation task, we used 1-tailed t-tests since we had a prediction about the direction of the effect based on the data obtained from the motion task.

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