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Visual Search and Spatial Deficits

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Abstract

Studies of visual search with patients with spatial attentional deficits have shown that the ability to bind basic features properly and thus to search for the conjunction of two spatially contiguous features is compromised. However, the effect of spatial deficits on feature search is more controversial. Here, we explore questions raised by the neuropsychological literature regarding feature processing and demonstrate that features “pop out” in the affected visual field, albeit more slowly. The implications for feature processing and selection as well as the relevance for understanding spatial deficits are discussed.

The neuropsychological literature has demonstrated that visual search for conjunctions becomes more difficult when visual spatial deficits are present, while feature search remains relatively intact. Perhaps the most dramatic example of this difference has been reported in patients with Balints syndrome produced by *bilateral* damage to the dorsal (occipital-parietal) processing stream of the cortex (see Balint, 1909; Friedman-Hill, Robertson & Treisman, 1995). When symptoms are severe, these patients see only one object at a time (simultanagnosia) and lose the ability to control which object will pop into view next. Another striking symptom is that they are unable to locate even the objects they do see (see Rafal, 2001; Robertson, 2004, for a more complete description of the syndrome). When forced to guess the object's location, they may protest or perform at chance levels (Friedman-Hill, et al. 1995). When asked to point to the object, they are unable to do so correctly, and their errors in spatial reports are unsystematic. These problems are isolated to space external to the body: locating sensation on the body is typically intact, as is the ability to move body parts in one direction or another on command (Robertson, et al., 1997).

Accompanying the spatial deficits are problems in properly binding features in perception such as color, size or motion and shape, producing illusory conjunctions (Bernstein & Robertson, 1998; Friedman-Hill, et al. 1995; Humphreys et al., 2000; Robertson, 2003). For instance, a red O and blue T might be perceived as a blue O and red T. These illusory conjunctions, which can be found in normal perceivers under data limited or controlled laboratory conditions (Treisman & Schmidt, 1982), are prevalent even under free viewing conditions in patients with Balint's

syndrome. When spatial attention is compromised, whether by laboratory manipulations or by neurological insult, correctly binding surface features together is also compromised.

It has also been argued that a binding problem that produces illusory conjunctions should also affect conjunction search (Feature Integration Theory - Treisman & Gelade, 1980, although see Desimone & Duncan, 1995, and Duncan & Humphreys, 1989, for alternative accounts). Indeed, this is the case. Robertson et al (1997) asked a patient with Balints syndrome (RM) to report whether or not a red X was present in 2, 4 or 6 item displays (Figures 1), a trivial task for normal perceivers with such small set sizes. The target was presented either with red O and blue X distractors (conjunction search) or with all Os or blue Xs (feature search). RM's responses were painfully slow when looking for conjunctions (up to 6 seconds), even in these small set size displays, and RT was quite variable. He made numerous errors, and the pattern of errors for features and conjunction search was most revealing. His miss and false alarm rates for feature search were similar (Table) and close to that of his miss rate (target present displays) for conjunction search. Consistent with his high number of illusory conjunctions, he made 38.3% false alarms in conjunction search (target absent displays). When the display contained red and blue and Xs and Os but no red X, he miscombined color and letter and reported seeing a red X on over a third of the trials. When asked if this is what he actually saw, he replied that it was.

INSERT TABLE 1 ABOUT HERE

INSERT FIGURE 1 ABOUT HERE

Patients with unilateral damage resulting in unilateral neglect¹ also have special difficulty searching for conjunctions², especially when the target is in their contralesional field (Eglin, Robertson & Knight, 1989; Eglin et al., 1994; Esterman, et al. 2000; Riddoch & Humphreys, 1987) This can occur even when difficulty or saliency between conjunction and

feature search is equated (Humphreys, 2003). This problem need not affect the rate of search on the contralesional side *per se* (see Figure 2), and can be attributed to a “contralateral delay” (up to 20 seconds or more) to begin searching the neglected side. The difference between intercepts for search functions on the spared³ and neglected sides increases as the number of distractors on the spared side increases. This difference can decrease when the distractors on the spared side are grouped (Robertson, Eglin & Knight, 2003). In other words, perceptual organization that reduces the number of functionally integrated items in the spared field can change the magnitude of the contralateral delay.

INSERT FIGURE 2 ABOUT HERE

Another important aspect of search with this patient population is that the contralateral delay does not reflect a simple bias to start search at a more ipsilesional point than normal and then scan continuously in the contralesional direction. There is something special about the midline that delays searching the neglected side. For instance, the search rate on the *spared* side in Figure 2 was estimated to be nearly 300 ms per item (slower than normal but systematically linear). At this rate, it should take about 3 seconds to begin searching the neglected side when 10 distractors appear on the spared side opposite the target, but instead it took over 7 seconds to do so. Even when patients knew there would *always* be a target in the display, they did not start searching the neglected side until scanning items on the spared side more than once. Critically, whether the intercepts between spared and neglected sides changed or not, serial search patterns for conjunctions were present. Response times increased linearly as a function of the number of distractors on the same side as the target in a group of patients with unilateral neglect (Eglin et al., 1989, 1994; Estermann, et al., 2000; Robertson et al., 2003).

Feature search can be different. When patients with unilateral parietal and/or frontal damage and neglect are asked to detect the presence or absence of a target with a unique feature, response times on the neglected side can be flat over set size, consistent with parallel search (Brooks, Wong & Robertson, in press; Esterman, et al., 2000, Laeng, Brennen & Espeseth, 2002; Riddoch & Humphreys, 1987). If these patients are asked to *locate* the target instead of giving a yes/no answer, non-zero slopes may appear, but the slopes are nowhere near as steep as those for conjunction search (Eglin et al., 1989, 1994). Nevertheless, whether there is a shallow or flat slope, intercepts on the neglected side are generally elevated relative to intercepts on the spared side. Despite this elevation, search rates can be similar to those observed in normal perceivers (Figure 3). These findings together suggest that features can be processed in parallel (pop-out) in the neglected field but reach detection threshold later than features in the spared field. The intercept differences between the spared and neglected sides in feature search suggest that dorsal damage also affects ventral processing. These findings are consistent with a proposal by Humphreys (1998) that in normal visual search intact parallel processing of item locations by the dorsal system gives a boost to parallel processing of features by the ventral stream through early interactions between dorsal and ventral pathways (Humphreys, 1998). The claim is that the spatial locations and colors of search items in the display are each processed in parallel through interacting dorsal and ventral streams, increasing the signal and speeding feature detection. If this is the case, then feature selection within the ventral stream should be slowed when spatial inputs are compromised. Parallel feature processing should still occur, but reach the threshold of awareness later.

INSERT FIGURE 3 ABOUT HERE

Features Pop-Out With or Without Intact Spatial Abilities. We directly tested the hypothesis that features are processed in parallel but that the time required to reach detection threshold is delayed in a patient (SV) with unilateral visual neglect due to right hemisphere damage. S.V. showed mild chronic neglect and extinction on standard neuropsychological tests⁴ even several years post stroke. Unlike previous studies using reaction time measures, we adopted a psychophysical staircase method to estimate the stimulus presentation time needed for SV to reach 75% percent correct detection (Kaernbach, 2000).

SV suffered a middle cerebral artery infarct in the right hemisphere affecting dorsolateral frontal areas and most of the lateral parietal lobe with extension into temporal-parietal junction and superior temporal plain. The lesion spared the ventral temporal areas, including areas that code color (e.g., V4/V8). Consistently, she had normal color vision as assessed by Dvorine Pseudo-Isochromatic plates. In addition, a computerized perimetry test showed that SV's visual fields were intact well within the visual angle of the displays.

The displays either contained 4 or 8 items presented on one side of fixation or the other (unilateral) or 8 or 16 items presented on both sides (bilateral). The search items were 1° in diameter Os presented equidistant from a central fixation cross (Figure 4), approximately 7.3° in the periphery (eye movements were monitored and trials when movements occurred did not contribute to the staircase threshold calculation). The probability of a target being present on any given trial was 50%. The subject's task was to report whether a target appeared or not in an unspeeded manner. Each trial was preceded by a 1000 ms fixation point in the center of the display, and the examiner sat opposite SV behind the computer to watch for eye movements and keyed in a code for those trials on which they occurred. These trials were less than 1%.

INSERT FIGURE 4 ABOUT HERE

Unilateral and bilateral conditions were blocked in 6 different sessions. Condition order was counterbalanced between sessions, and separate thresholds were estimated for each side of the display for each condition in each block⁵. The staircases for the two sides of the display were interleaved so that the probability of a target on the two sides was equal within each block. The display at the start of each block was presented for 800 ms, the time decreasing or increasing over trials contingent on SV's response until 10 reversals occurred for each side of the display. Threshold estimates were recorded for each session and based on the last 8 reversals for each side independently. The computer refresh rate limited the minimum threshold and the time increments and decrements to 10 ms. Each block lasted between 5 and 10 minutes.

INSERT FIGURE 5 ABOUT HERE

As shown in Figure 5, the hypothesis was confirmed: the number of distractors on the same side as the target made virtually no difference in threshold presentation time. Consistent with SVs left neglect, threshold presentation times for unilateral displays were longer when the target was in the affected field (left visual field or LVF) than when it was in the right visual field (RVF), and bilateral displays increased thresholds for the LVF even more (an extinction like pattern). The number of distractors in the RVF made virtually no difference in the magnitude of this increase. Displays had to be presented for over 200 ms longer when the display was bilateral and targets were in the LVF than when targets and distractors were presented in the LVF alone.

Implications for Neglect and Extinction. Unilateral neglect is generally defined as missing information on the contralesional side of space even when stimulation is confined to only that side, and extinction as missing information on the contralesional side only under double simultaneous stimulation. For instance, a patient might be asked to point to the side or sides of stimulation when they see an examiner move something in the patient's right and/or left visual

field (such as the examiner's fingers). These effects are seldom all or none (as long as primary visual areas are intact). That is, patients may miss 60% of contralesional stimulation on unilateral trials and 90% on bilateral trials. In this way, a patient can be said to suffer from both neglect and extinction. SV's clinical profile conformed to this pattern, and her thresholds in our study did as well. Distractors increased LVF thresholds even when there was no evidence for a serial scan through displays. Perhaps surprisingly, improved grouping by proximity (created by doubling the number of distractors) had no effect on these thresholds. The effect of proximity on grouping is well known and has been shown many times (see Palmer, 1999, for a thorough discussion). Even though bilateral displays with 16 distractors formed a better circular configuration than those with 8, proximity (density) of the items in the display had no effect on threshold detection time.⁶ RVF distractors increased threshold, but again it did not matter whether they were sparsely or densely packed. Thus, the amount of color (i.e., red) in the RVF was not as important as its mere presence, and items that grouped into a better circle made no difference.

SV's lesion did not extend into primary visual areas or into ventral areas associated with color processing. Nevertheless, more dorsal lesions appeared to compromise the function of these ventral areas. In SV's case it directly affected feature encoding on the same side as the lesion, slowing feature detection overall, consistent with her neglect.

Implications for Visual Search. The thresholds observed with SV are consistent with reaction time studies reported in the neuropsychological literature suggesting that features can be processed in parallel on the neglected/extinguished side, although speed of processing might be slowed. An important new finding is derived from the difference in thresholds between unilateral and bilateral displays. Feature displays limited to the LVF (and thus projected to the

damaged right hemisphere) were slowed in reaching target detection threshold. But even longer display presentations were required when distractors were added to the RVF. This pattern was evident despite the fact that cortical areas associated with color perception (Zeki, 1980) were spared and were anatomically and functionally intact in SV.

One could argue that distractors on the right attracted attention, slowing attentional allocation to the left side, and thus the feature target did not truly “pop-out”. But there are reasons to reject this argument. First, there was no evidence that increasing the color signal (i.e., number of distractors) within a visual field affected LVF thresholds (A compared to B and C compared to D in Figure 5. These results are consistent with parallel feature processing in specialized color processing areas within the ventral stream of the contralateral hemisphere that is simply slower to reach threshold. Second, when the number of distractors was the same (B compared to C), their distribution across the two fields decreased detection in the LVF dramatically, which would not be expected with a serial search or even an inefficient parallel search for features. However, the results are consistent with feature processing interactions between the two hemispheres. The fact that there are specialized areas for color processing in each hemisphere suggests the existence of two color maps that under normal circumstances communicate without a spatial bias. In fact, there is clear fMRI evidence that ipsilateral stimulation activates V4, although less than contralateral stimulation (Tootell et al, 1998), providing ample evidence in normal perceivers for this type of interaction.

In the case of SV the items projected to the left hemisphere (RVF) inhibited feature detection in the LVF. This does not mean that spatial selection was necessary for feature detection, but rather that the fidelity or speed of the information processed by the intact ventral stream of the damaged hemisphere can be decreased by both a reduced spatial signal due to

dorsal damage of the same hemisphere (Figure 5A vs 5B) and a change in the feature signal from the opposite hemisphere (Figure 5AB vs 5CD). The prior entry of RVF items slowed detection of LVF targets, presumably through callosal interactions.

Invoking a serial search for the target (even a global serial search from one side to the other) is not required to account for these findings. Rather, we can expand on Humphreys (1998) claim that in normal feature search, parallel spatial and feature processing in dorsal and ventral streams respectively interact to “boost” the strength of search items. In this model, there is mutual facilitation. The present findings add an additional influence from the opposite hemisphere that appears to be inhibitory. In the case of SV, right dorsal damage would produce an overall disruption in this system by reducing the normal boost in feature processing in the same hemisphere, which in turn would reduce the strength of the signal across the callosum. This would lead to an imbalance between right and left signals that are normally mutually inhibitory.

Note that both of these models are consistent with parallel feature processing and the predictions of feature integration theory that spatial or focal attention is not necessary for feature detection (Treisman & Gelade, 1980). They are also at least partly consistent with biased competition models of visual search (Desimone & Duncan, 1995), at least at the spatial resolution of competition between hemispheres for processing resources. In this case, the competition is for a specialized population of neurons (presumably in the temporal lobe) that encode color features on the left and right of a visual display.

Conclusions. There has been much speculation about whether spatial attention is involved in feature search. Are search slopes shallow because a fast scan can be made when targets are salient? The neuropsychological literature on visual search in patients with spatial

deficits suggests that the answer is no. In fact, features (but not conjunctions) can be detected with nearly complete loss of spatial information of the external world (e.g., Balints syndrome). However, feature processing is not entirely normal in these cases even when ventral processing streams are intact. We have shown that thresholds for feature detection do not increase within each visual field with added distractors for a patient with chronic neglect and extinction. However, such displays must be presented longer to reach contralateral thresholds and longer still when bilateral displays are presented. Clearly, spatial information is not required for feature search to occur in parallel. However, spatial information does influence the amount of time that it takes to resolve feature processing independently of the number of distractors present.

These findings are consistent with early dorsal interactions with parallel feature processing in ventral streams as well as with strong interactions between specialized feature processing areas across hemispheres. When unilateral damage and neglect are present, the normal interactions between these areas are compromised.

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Figure Captions

Figure 1. Example of search displays with the target present that was used to study feature search (left) and conjunction search (right) in a patient with Balints syndrome. Displays were chromatic and the patient was asked to detect the presence or absence of the red X (Black represents red and gray represents blue).

Figure 2. Mean response time (in seconds) for a group of patients with unilateral neglect to detect a conjunction target on the neglected and spared side of a search display as a function of the number of distractors on the target side and the number on the opposite side (adapted from Eglin, et al., 1989).

Figure 3. Feature search for a group of patients with left neglect and right hemisphere damage and a group of normal controls when searching for a Q among Os (i.e., the presence of the tail of the Q). Mean response time for feature search in the contralesional (left) and ipsilesional (right) sides of a display as a function of set size. (Figure provided by Michael Esterman based on data reported in Esterman et al., 2000).

Figure 4. Example of unilateral and bilateral displays. The target was a green (black) circle among red (gray) circles. Displays were either dense (top) or sparse (bottom)

Figure 5. Mean threshold stimulus presentation times to produce 75% correct feature detection for patient SV. Thresholds are shown for left visual field (LVF) and right visual field (RVF) for unilateral and bilateral displays. Patterns at the bottom are cartoons that represent displays with a LVF target.

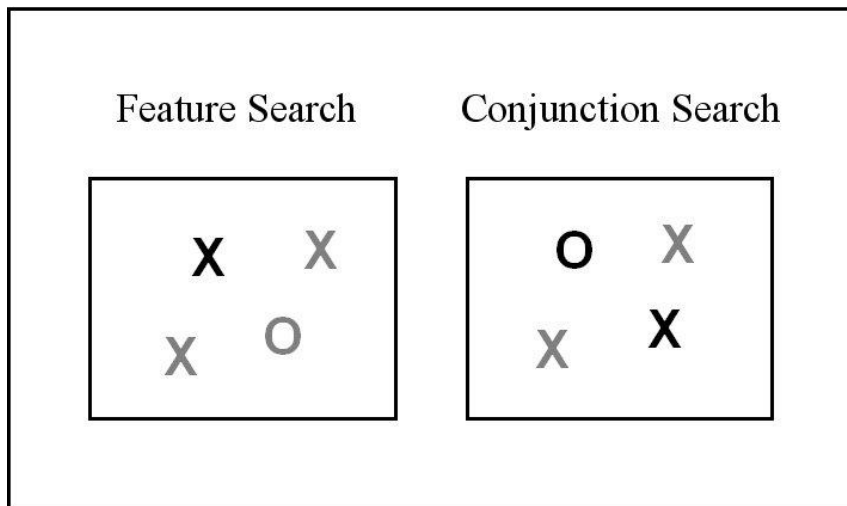


Figure 1

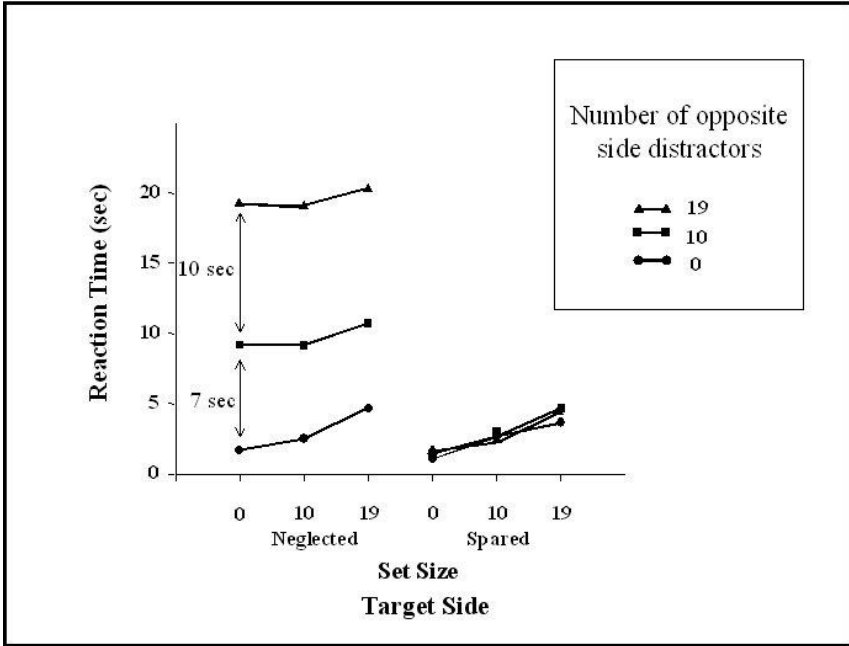


Figure 2

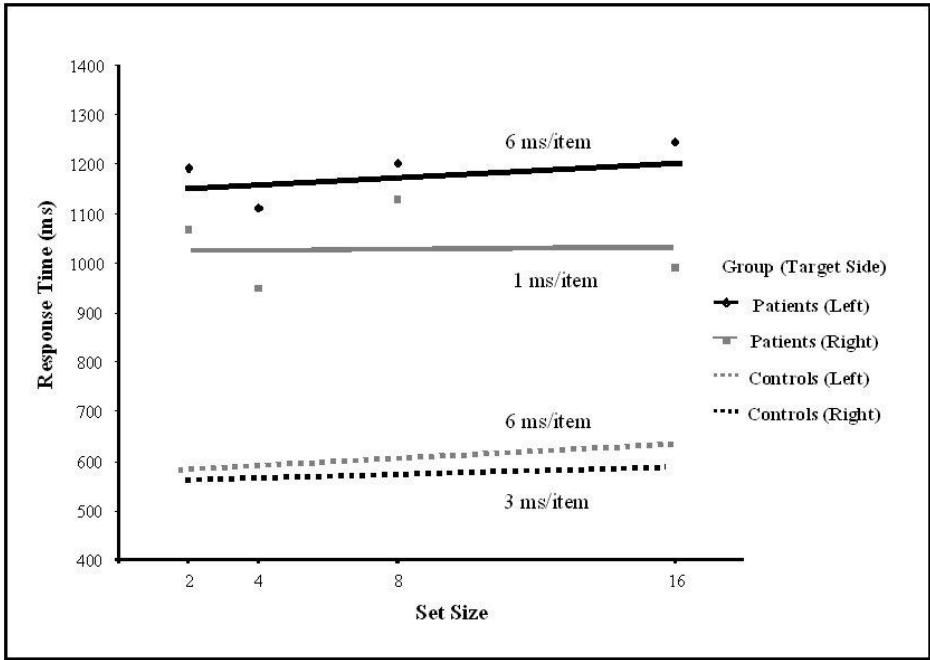


Figure 3

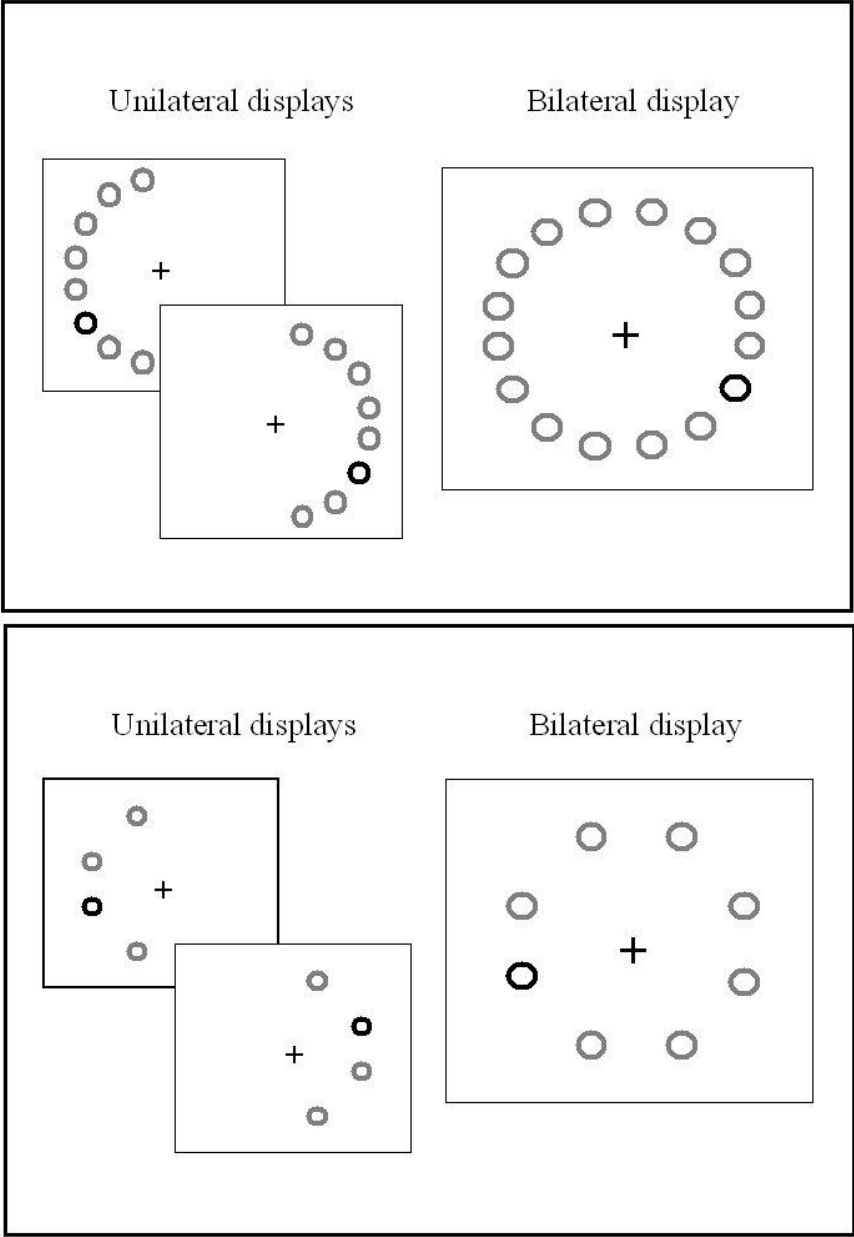


Figure 4

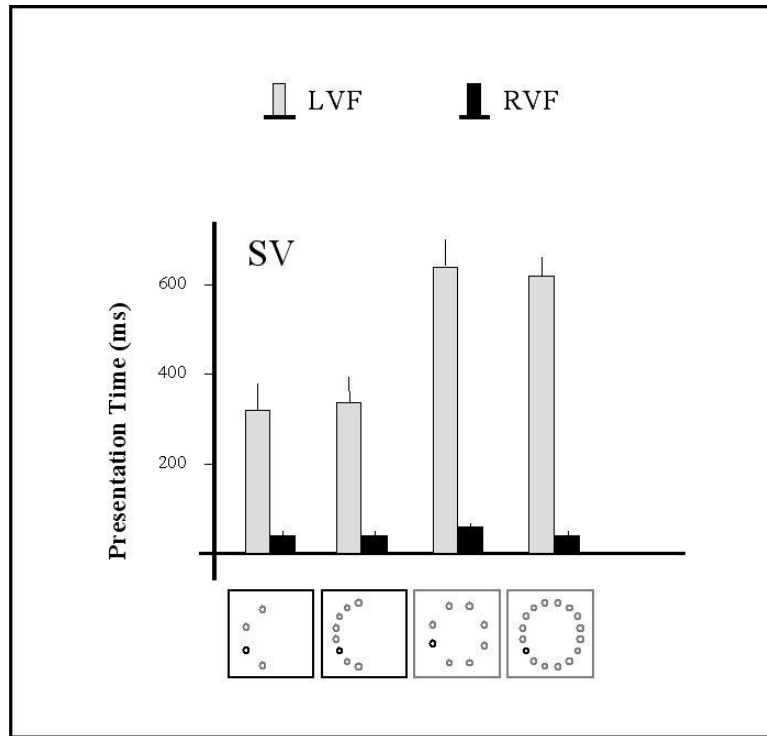


Figure 5

Percent Errors		
	Feature	Conjunction
Misses	4.0%	4.0%
False Alarms	1.3%	38.3%

Table 1 Percent misses and false alarms for Feature and Conjunction search for patient RM with Balints syndrome.

¹ Unilateral visual neglect as defined clinically does not necessarily mean that a patient *never* attends to the contralesional side of space. They typically can be cued to attend to this side, and rehabilitation measures often include training patients to cue themselves accordingly.

² also see Cohen & Rafal (1991) for evidence of illusory conjunctions on the neglected side of space in a patient with unilateral right neglect from left hemisphere damage

³ We will refer to the ipsilesional, non-neglected side as the “spared” side, but this is not quite correct. Search rates were slower on both the ipsi and contra lesional sides than normal, age-matched participants in the data reported by Egin et al. (1989). Search in the ipsilesional side occurred first with a disproportionate delay to begin search on the contralesional side.

⁴ SV showed symptoms of chronic visual neglect since the time of her stroke several years prior to testing in the present experiment. She was again administered a standard battery for neglect shortly before the present experiment was run. She bisected horizontal lines an average of 5 cm to the right of center, extinguished all the left items in a 2-item display and missed $\frac{3}{4}$ of the left items when only 1 item appeared either to the left or right of center. She also demonstrated visual extinction and neglect on standard bedside confrontation testing. Due to travel limitations, a perimetry test of visual fields was performed on a laptop computer by presenting a 0.3° blue circle briefly on a white background. The circle only appeared after she responded to a central mark that was difficult to detect unless fixated. This procedure assured central eye fixation. SV sat approximately 60 cm from the screen, and was asked to press a key on the mouse as soon as she detected a target. The target could appear in one of a total of 44 locations spanning the monitor screen, 10 times in each location.

⁵ Presentation time was adjusted in increments of $\Delta T = 6 - [(r+1) - \text{mod}((r+1),2)]/2$ screen frames, where r = the number of reversals encountered and $\text{mod}(a,b)$ is the remainder after division of a by b .

⁶ Eight naïve individuals were asked to judge which of the bilateral figures created the better circle or whether both were the same. All eight chose the dense patterns over the sparse patterns without hesitation.