

Research Article

Independent Resources for Attentional Tracking in the Left and Right Visual Hemifields

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ABSTRACT—*The ability to divide attention enables people to keep track of up to four independently moving objects. We now show that this tracking capacity is independently constrained in the left and right visual fields as if separate tracking systems were engaged, one in each field. Specifically, twice as many targets can be successfully tracked when they are divided between the left and right hemifields as when they are all presented within the same hemifield. This finding places broad constraints on the anatomy and mechanisms of attentive tracking, ruling out a single attentional focus, even one that moves quickly from target to target.*

The brain is divided into separate left and right hemispheres that are connected by the corpus callosum, a large network of fibers that communicates information between the hemispheres (Myers & Sperry, 1958; Sperry, Gazzaniga, & Bogen, 1969). Incoming visual information from the left half of the visual field projects to the visual cortex in the right hemisphere, and information from the right half of the visual field projects to the visual cortex in the left hemisphere. This division of the visual fields is evident in early stages of cortical processing (areas V1–V5, middle temporal area), in which receptive fields are unilateral and limited to the contralateral visual field (cf. Bullier, 2004). The separate processing of the information in the two hemifields gives way to bilateral processing at higher levels (areas in the inferotemporal and parietal cortex; Bullier, 2004), where information from both hemifields is represented in each hemisphere. The hemifield of the input has little influence on most high-level tasks, especially those involving attention (Arguin, Joanette, & Cavanagh, 1990; Duncan et al., 1999). There are, of course, well-known hemifield

advantages due to the differential processing of specific materials in one or the other hemisphere (e.g., language in the left hemisphere—Kimura, 1973; metric spatial relations in the right hemisphere—Kosslyn, 1987); however, these effects, although measurable and important, are moderate in the normal observer, as information from either hemifield eventually ends up in the specialized hemisphere via the corpus callosum, with only a modest cost in processing times or efficiency. With the exception of split-brain patients, then, the effects of the hemifield in which information is presented are small, as the connected hemispheres have evolved to efficiently integrate information across both visual fields.

Here we report an exception to this overall pattern of successful integration of the two hemifields. Moreover, it is an exception in a seemingly high-level task: tracking multiple targets with attention. Specifically, we show that each hemifield imposes independent constraints on attentional selection, such that twice as many targets can be tracked when the targets are divided between hemifields as when they are all presented within the same hemifield. Previous studies have suggested that there are independent attentional capacities in the left and right cerebral hemispheres of split-brain patients, leading to faster processing of bilateral displays relative to unilateral displays (Luck, Hilliard, Mangun, & Gazzaniga, 1989). We now provide the first evidence for independence in the capacity to attentively track targets in the left and right visual hemifields in normal, healthy observers.

EXPERIMENT 1

In this experiment, two rotating sinusoidal gratings were presented on each trial, either both in the same visual field or one in each field (Fig. 1a). The black wedges of the grating formed an X shape with two orthogonal “bars” (the hourglass shape formed by two wedges on opposite sides of the center of the grating). Observers were asked to keep track of one bar in one of the Xs or one

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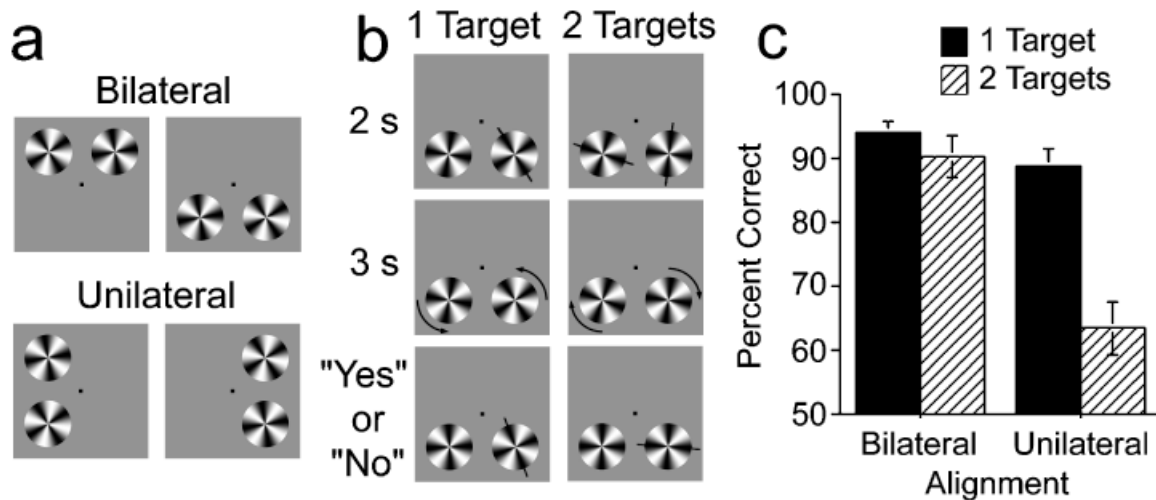


Fig. 1. Displays (a), example trial sequences (b), and results (c) of Experiment 1. On each trial, two X shapes (sinusoidal luminance gratings) were presented, in one of four arrangements: aligned bilaterally above or below fixation, or aligned unilaterally left or right of fixation. During the first 2 s of the trial, a line indicated the target or targets; the Xs then rotated for 3 s before a probe was marked by a line. The task was to indicate whether the probed bar matched the initial target. The graph shows tracking accuracy as a function of display type and the number of targets (error bars show ± 1 SEM).

bar in each X (Fig. 1b). Eye movements were not monitored, but observers were instructed to keep their eyes focused on the central fixation point and to “mentally” track the target bars as they rotated. The speed of rotation was adjusted for each observer so that tracking one target was taxing but successful on most trials (about 90% accuracy). Tracking one target at this level of difficulty requires continuous attentional selection, so that tracking a second target ought to degrade performance substantially if both targets draw on the same, limited attention resources. The question of principal interest was whether the cost of tracking a second target would be the same when the two targets were in the same visual field as when they were in different visual fields.

Method

Participants

Eight observers (including author G.A.A.) participated. All observers in this and subsequent experiments gave informed consent and reported normal or corrected-to-normal vision.

Stimuli

The stimuli were high-contrast, sinusoidal radial gratings. On each trial, a fixation point (black circle, radius = 0.2°) and two vertically or horizontally aligned gratings (radius = 3°) were presented; each grating was centered at a corner of an imaginary square subtending $8.5^\circ \times 8.5^\circ$, such that each corner was 6° from the fixation point. On bilateral trials, the stimuli were both either above or below fixation, and on unilateral trials, the stimuli were both either to the left or to the right of fixation (see Fig. 1a). The distance between the vertical and horizontal meridians and the nearest edge of each grating was 1.25° . The gratings rotated at an average rate of $218^\circ/\text{s}$ (see Procedure). On each trial, the initial

direction of rotation (clockwise or counterclockwise) was randomly determined independently for each grating, and throughout the trial, the gratings changed direction of rotation; the direction changes for each grating were determined randomly and independently of those for the other grating.

Procedure

At the beginning of each trial, a target bar was marked for 2 s with a line; then the marker disappeared, and both gratings rotated for 3 s (see Fig. 1b). At the end of the trial, a probe bar was indicated with a line, and observers indicated whether that bar was the same bar as the initial target for that grating. Because the gratings rotated and changed direction randomly, the orientation of the target bar at the end of the trial was independent of its initial orientation, so the only way to perform this task was to mentally track the target bar as it rotated so that it could be identified at the end. If two targets were tracked, only one was randomly selected and probed. During a preliminary set of trials, each observer tracked one target at speeds ranging from $100^\circ/\text{s}$ to $650^\circ/\text{s}$, and the speed that yielded 87.5% correct in the tracking task was estimated by linear interpolation separately for each observer. The rotation rate in the test phase of the experiment was set to this threshold speed. Observers completed 128 practice trials and 128 test trials.

Results and Discussion

Figure 1c illustrates the results. Observers were able to track a single target accurately on nearly 90% of the trials whether the two gratings were aligned bilaterally or unilaterally, as set by the threshold procedure. The critical finding is that there was a large drop in accuracy when the number of targets increased from one to two within the same hemifield, $t(7) = 6.45$, $p < .001$,

$d = 2.62$, but no significant difference in accuracy when multiple targets were tracked in separate hemifields, $t(7) = 0.90, p = .40, d = 0.48$.

One can predict the tracking accuracy expected if only one target can be tracked by assuming that in the two-target condition, one target is tracked as well as it would be alone, whereas the other target is not tracked at all. When one of the two is randomly tested, on half of the trials, the tracked target will be probed, and accuracy will be equal to single-target accuracy; on the other half of the trials, the untracked target will be probed, and performance will be at chance (50%). This simple model predicts that if only one target can be tracked, the percentage of correct tracking for two targets will be 72% in the bilateral displays and 69% in the unilateral displays. This level of performance was clearly exceeded in the bilateral displays (90% observed, 72% predicted), $t(7) = 5.63, p < .001, d = 2.71$, but accuracy when the two targets were presented unilaterally was consistent with this prediction (63% observed, 69% predicted), $t(7) = 1.48, p = .18, d = 0.70$. This result suggests that when both targets were presented within a single hemifield, tracking of one target was accurate, and performance on the second target was at chance. Thus, the results of Experiment 1 are consistent with the existence of independent resources for attentional selection in the two visual hemifields and shared resources within a hemifield.

EXPERIMENT 2

In Experiment 1, the unilateral targets were vertically aligned with respect to each other, whereas the bilateral targets were horizontally aligned. Thus, it is possible that the results reflect a horizontal advantage in attentive tracking, rather than independent resources for the two hemifields. We controlled for this possibility in Experiment 2 by requiring observers to track targets that were either vertically or horizontally aligned, but were always presented entirely within a single hemifield (see Fig. 2a).

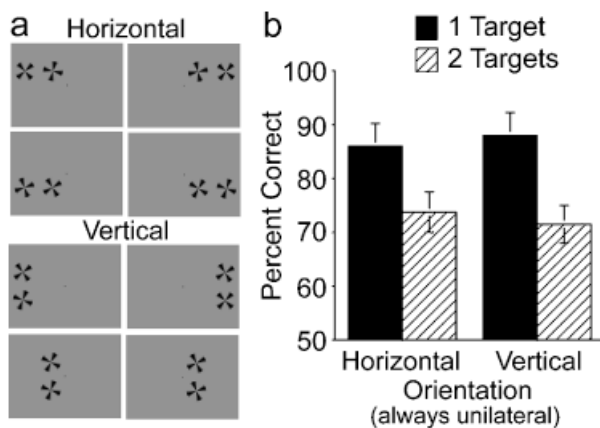


Fig. 2. Displays (a) and results (b) of Experiment 2. On each trial, two radial gratings were presented in one of eight possible arrangements; the two gratings were aligned horizontally or vertically, always within a single hemifield. The graph shows tracking accuracy as a function of display type and the number of targets (error bars show ± 1 SEM).

If the previous results were due to a horizontal advantage in attentive tracking, then performance in Experiment 2 would be expected to be better for horizontal targets than for vertical targets.

Method

Participants

Eight naive observers participated.

Stimuli

The radial gratings were half-wave rectified (luminance values above the mean were set equal to the mean), because during pilot testing, this reduced the effects of crowding when observers tracked horizontally aligned targets (when they tracked a single target, there was no significant difference in tracking between the target nearer fixation and the target further from fixation; see Fig. 2a). Two gratings were always presented, both within a single half of the visual field. On horizontal trials, two gratings were presented on the top left, top right, bottom left, or bottom right (Fig. 2a). On vertical trials, two gratings were presented on the far left, far right, near left, or near right (Fig. 2a). For both trial types, the grating locations corresponded to the corners of an imaginary square subtending $8.5^\circ \times 8.5^\circ$, with the center of the square shifted 4.25° to the left or right of fixation so that all four corners fell within one field. The speed of rotation was set to $120^\circ/\text{s}$.

Procedure

The tracking procedure of Experiment 1 was used to test performance with one or two targets always displayed unilaterally (horizontally or vertically).

Results and Discussion

Figure 2b presents the results. Tracking accuracy for horizontally and vertically aligned targets did not differ either when one target was tracked, $t(7) < 1, p = .52, d = 0.23$, or when two targets were tracked, $t(7) < 1, p = .44, d = 0.23$. Thus, there was no advantage for tracking horizontally aligned targets over tracking vertically aligned targets in this experiment. Moreover, not only was tracking accuracy lower for two targets than for a single target in unilateral displays, as in Experiment 1, but in the case of Experiment 2, this drop in accuracy was seen for both horizontally aligned targets, $t(7) = 3.78, p < .01, d = 1.41$, and vertically aligned targets, $t(7) = 4.29, p < .01, d = 1.62$. The level of performance when the two targets were presented either horizontally or vertically is consistent with accurate tracking of one target and chance performance on the second target. The drop in accuracy for two horizontally aligned targets presented within a single hemifield cannot be explained by a disadvantage in tracking more-peripheral targets because there was no significant difference in tracking accuracy for near and peripheral targets when only a single target was tracked—horizontal: $t(7) =$

2.22, $p > .05$, $d = 0.80$; vertical: $t(7) < 1$, $p > .05$, $d = 0.07$. In Experiment 1, there was no performance cost for tracking two targets when they were aligned horizontally, so the critical factor in that experiment cannot have been the horizontal alignment, but must have been the separate placement of the two targets in the left and right hemifields.

EXPERIMENT 3

It was important to verify that a different type of tracking task would also yield evidence for independent limits in the left and right hemifields. Thus, we repeated the experiment with a task requiring observers to track the positions of a subset of several identical moving targets (Pylyshyn & Storm, 1988). On each trial, observers were required to keep track of two targets within a single quadrant or four targets in two separate quadrants (Fig. 3a).

Method

Participants

Eight naive observers participated.

Stimuli

The displays consisted of four black quadrants (subtending $14^\circ \times 10^\circ$) separated vertically and horizontally by 1.25° (the area between quadrants was gray). On each trial, a fixation point (a small black circle subtending 0.4°) and eight green discs (diameter = 1.25°) were presented. Four discs were randomly placed within each of two quadrants (above, below, left, or right of fixation) with a minimum spacing between circles of 3° , such

that the eight discs were displayed bilaterally (above or below fixation) on some trials and unilaterally (right or left of fixation) on other trials (see Fig. 3a).

The discs moved at a constant speed of $15^\circ/\text{s}$, repelling other discs and changing direction when closer than 3° to another disc or when touching the edge of a quadrant. The speed was selected on the basis of pilot experiments showing that observers can track two targets with about 90% accuracy at this speed. Discs were repelled by other discs in their own quadrant and by the borders of the quadrant in which they were presented, but moved independently of discs in the other quadrant; thus, the motion trajectories of items in the two quadrants were independent and uncorrelated.

Procedure

As illustrated in Figure 3b, two or four target discs were marked for 2 s (unfilled discs) at the beginning of each trial. Then all of the discs became identical and began to move at a constant rate of $15^\circ/\text{s}$ for 5 s. At the end of each trial, regardless of whether the observer was tracking two or four discs, a single, randomly selected disc was marked, and the observer indicated whether or not it was one of the original targets. Observers completed 128 practice and 128 test trials.

Results and Discussion

The results replicated those of Experiment 1 (see Fig. 3c). Observers tracked two targets accurately on about 90% of the trials whether the two sets of discs were aligned bilaterally or unilaterally. When the number of targets increased from two to four, there was a large, significant drop in accuracy when the targets

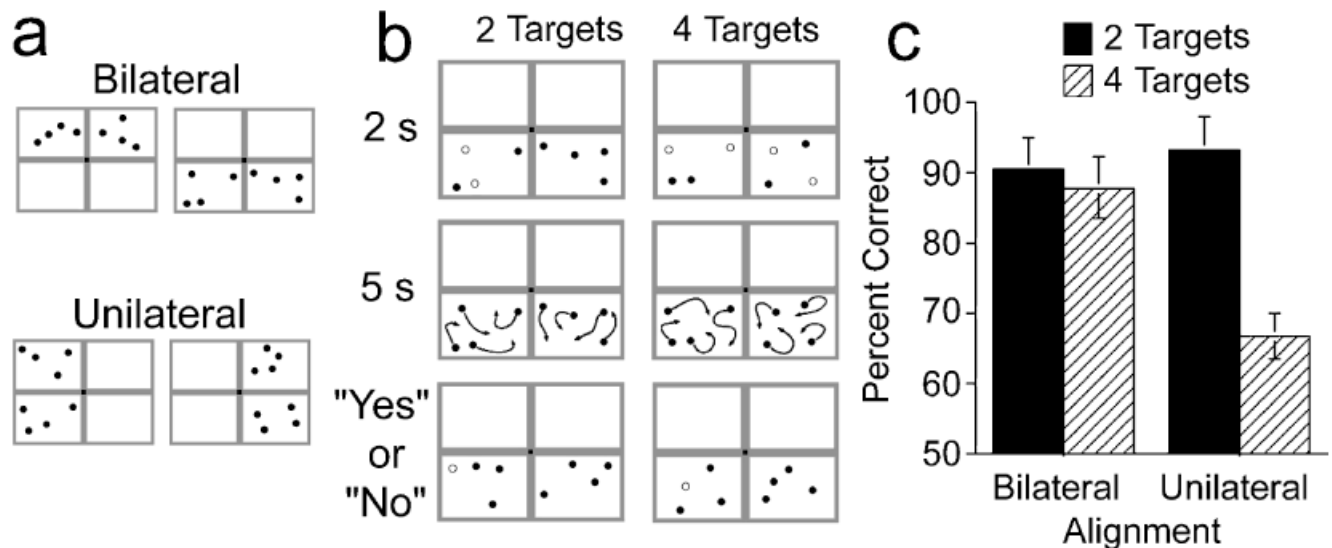


Fig. 3. Displays (a), example trial sequences (b), and results (c) of Experiment 3. On each trial, two sets of four discs were presented, in one of four arrangements: aligned bilaterally above or below fixation, or aligned unilaterally left or right of fixation. During the first 2 s of the trial, two or four targets were indicated (shown as unfilled circles here); the discs then moved for 3 s before a probe disc was marked (shown as an unfilled circle here). The task was to indicate whether or not the probe was one of the original targets. The graph shows tracking accuracy as a function of display type and the number of targets (error bars show ± 1 SEM).

were presented within a hemifield, $t(7) = 5.49, p < .01, d = 2.98$, but not when they were presented in separate hemifields, $t(7) = 1.59, p = .16, d = 0.35$. The observed accuracy levels are consistent with the level of performance expected if only two targets can be tracked within a field but four targets can be tracked without cost in opposite hemifields (predictions based on the simple model described in Experiment 1).

These results provide converging evidence that there are independent limits on attentional selection for the left and right visual hemifields. Note also that the number of items that could be tracked at the criterion level (about 90%) was set to two in this experiment, rather than one as in the previous experiments. The target speed was adjusted in each experiment to arrive at the criterion performance level, and the data show that the capacity for tracking can be increased by decreasing the speed of the items, although there is probably an upper limit on the number of targets that can be tracked even at very slow speeds.

GENERAL DISCUSSION

The results of these experiments strongly suggest that there are independent resources for attentional tracking in the left and right visual hemifields. In Experiment 1, twice as many targets could be tracked when they were presented in opposite hemifields as when they were presented within a single hemifield. The possibility that the alignment of the targets explains the results was ruled out by Experiment 2, in which horizontal alignment was not sufficient for multiple targets to be tracked within the same hemifield. At the speeds tested in Experiments 1 and 2, it appears that the targets had to be located in opposite hemifields in order for observers to track them both. Finally, Experiment 3 provided converging evidence for the independence between visual fields using a task that required tracking multiple objects in each field.

On the basis of these results, we claim that there are independent resources for attentional tracking in the two hemifields. However, it is important to consider two alternative explanations: attentional crowding and perceptual grouping. First, one could argue that lateral inhibition or crowding between items is greater within a hemifield than between hemifields, and that this difference in crowding explains the current results. However, some aspects of the data are inconsistent with this claim. First, previous research has shown that crowding is greater in the upper visual field than in the lower visual field (He, Cavanagh, & Intriligator, 1996), but there was no difference in tracking accuracy between the upper and lower visual fields in the current experiments. This suggests that crowding was not a major factor in tracking performance with these displays. Instead, tracking accuracy appears to have been limited by the updating demands set by the speed of the moving targets. Another reason to discount the crowding explanation is that we found substantial differences in performance without changing the physical appearance of the display. For example, in Experiment 1, performance dropped substantially when the number of targets within a field increased

from one to two, but the display was exactly the same whether one or two targets were tracked. Thus, the drop in accuracy appears to be explained by an increase in attentional load.

The second possible alternative explanation that we must address concerns the perceptual grouping of targets. Many observers note that, phenomenologically, tracked objects form an integrated hierarchical shape (Yantis, 1992). It is possible that it is easier to group multiple items together into such a global shape when they are in opposite hemifields than when they are presented within a single hemifield. However, there are several reasons to believe this was not the case in our experiments. First, our stimuli did not have any similarities or symmetries that would encourage grouping (no common motion, and for the X s, no common orientation). The items in each quadrant always moved independently of items in the other quadrants, with no correlation between targets in direction of motion or changes in direction of motion. Second, the hypothesis that grouping is stronger across hemifields than within a hemifield is inconsistent with other research suggesting that the opposite is true—that the strength of low-level perceptual interactions is stronger within a hemifield than across hemifields (Butcher & Cavanagh, 2004; Pillow & Rubin, 2002).

Although we do not see how grouping could aid in the initial selection of multiple targets in our tasks, grouping could be a consequence of selection. Specifically, one potential effect of attentional selection is to form a perceptual group of items that otherwise have no attributes in common. Here we need to distinguish between low-level, feature-based grouping, in which grouping between items might precede selection (e.g., items grouping with other items of the same color), and high-level attention-based grouping, in which multiple, independent items with no low-level similarities are selected and then integrated to form a perceptual group. If one purpose of selection is to impose such high-level groupings between otherwise unrelated items, our results suggest an important constraint on such integrative functions: The number of items that can be grouped is independently limited in the two hemifields (the two hemifield-limited selections can then be integrated into one group). Critically, this view holds that the perceptual group is the output of an integrative function, and that independently selected items are the input to this function. In other words, the independent selections precede the grouping, rather than the grouping preceding selection. According to this proposal, the independent limits for the two hemifields reflect limits on the initial selection of targets, not on the subsequent grouping of targets.

Beyond demonstrating this important division of resources for attentional tracking, these results also have important implications for the mechanisms of tracking (e.g., how the control of tracking might be transferred from one hemifield to the other) or, more broadly, for the architecture of visual attention. Specifically, the ability to track multiple items has been used to argue that attention can have as many as four simultaneous, unconnected foci (Intriligator & Cavanagh, 2001; Pylyshyn & Storm,

1988). This claim has remained controversial. Even though there are four independently moving targets in a multiple-object-tracking display, some researchers argue that attention selects them as a single object with four vertices undergoing nonrigid transformations (Yantis, 1992). The introspections of observers support this view, as many report that they are tracking a non-rigid quadrilateral. However, our finding that tracking capacity is limited independently in the two hemifields requires that if the items are grouped into a single, higher-level object, it must be at a subsequent stage of integration. Two sets of vertices within that object must be selected independently within each hemifield (suggesting that tracking is optimal when the observer follows the center of the object, placing half the vertices in each hemifield). The grouping of the four vertices must follow the selection, rather than support selection.

A second counterproposal to the multiple-foci account is that there is only one focus (Eriksen & Yeh, 1985; Posner, 1980) that moves rapidly from target to target, returning quickly enough to the former location of each target to find its new location with reasonable success. Pylyshyn and Storm (1988) have argued that this rapid serial allocation would be problematic, but until now, there has been no empirical evidence that convincingly rules it out. However, the serial-allocation account relies on only one focus of attention and so has no mechanism to produce any hemifield independence. If the speed of moving from one item to the next is sufficient for keeping track of only two items when they are in one hemifield, it cannot double when these first two items are joined by another two in the other hemifield. But this is what the data would require. If serial scanning does operate, then, it must do so independently in the two hemifields, with a minimum of one focus of selection in each hemifield. The finding of hemifield independence therefore appears to rule out the remaining proposals that there is a single focus of attention.

Why does attentional tracking show this degree of hemifield independence in normal, healthy observers even though other capacity-limited processes, such as visual search (Luck et al., 1989) and memory storage (Duncan et al., 1999), do not? Although the current experiments do not directly address this question, we offer two speculative explanations. First, we assume that attentional processing is a chain of capacity-limited operations, beginning with target selection and then proceeding to higher-level processes such as identification and memory storage. Perhaps only the first step in attentional processing, that of selection, shows hemifield independence, whereas subsequent central stages deal with information from both fields. Thus, tasks that are more limited by later processing stages than by selection might not show hemifield independence, as central processing delays will provide time for serial target acquisition (thus bypassing the selection limit). According to this explanation, attentive tracking must be dominated by limits imposed at the selection stage, placing minimal demands on central operations such as identification and memory storage. Second, the visual system may have separate streams for processing identity infor-

mation and spatial information (the classic “what” and “where” distinction in vision; Ungerleider & Mishkin, 1982). According to this view, tracking involves attention to spatial location, whereas those visual search and memory tasks that have not shown hemifield independence involve attention to identity information. These explanations of why only attentional tracking appears to exhibit this degree of hemifield independence are not mutually exclusive; it is possible that both the stage of processing and the type of information being processed play an important role in determining whether independence between the hemifields is observed.

What is clear from the current experiments is that the ability to attentively track moving objects is independently limited in the two hemifields. To our knowledge, this is the first demonstration of substantial hemifield independence in any type of attentional processing for observers with an intact corpus callosum. Given the importance of the ability to keep track of multiple objects in everyday activities (e.g., driving, crossing busy streets, keeping track of one’s children) and the central role this ability plays in theories of cognitive development (Carey & Xu, 2001) and the architecture of vision (Pylyshyn, 1998), these results are likely to have important practical and theoretical implications.

Finally, similarities in capacity limits have been used to argue that different systems have a common underlying limit of about four items (e.g., for working memory and attention—Cowan, 2001; for subitization and multiple-object tracking—Pylyshyn, 1998). However, the current results suggest that in the case of the limits of attentional tracking, the magic number is not four, but two plus two. The dissociation between tracking tasks with a capacity of two plus two and other tasks (without hemifield independence) with a capacity of four suggests that the limit of four reported for a range of tasks is not due to a common bottleneck (other researchers have come to similar conclusions; Daneman & Carpenter, 1980; Halford, Wilson, & Phillips, 1998; Miller, 1956). However, we argue that sharing a common limit is not a coincidence either. A chain of attention processes that passes information from one stage to the next would have little use for local capacity that is not matched to capacities all along the chain. In this sense, the limit of four is more appropriately seen not as a single bottleneck, but as the matched bandwidth of a series of capacity-limited stages in attentional processing.

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