

## Attentional Limitations in the Sensing of Motion Direction

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Attentional constraints in the perceptual analysis of motion direction were examined using two independent paradigms: redundant target visual search and the analysis of fluctuations in discrimination accuracy at threshold. Results from both methods implied that directions of object motion are analyzed in parallel when those motions are translations, independent of the observer's line of sight. The registration of rotation direction appears to be subject to a qualitatively different protocol, one that is highly capacity limited and serial-like. These results suggest that scene-based descriptions, as opposed to image-based descriptions of motion, mediate the allocation of attention. © 2001 Academic Press

Motion occupies a privileged position among perceptual attributes by virtue of the sensitivities that humans and other mammals have for optic flow. Optic flow patterns are not typically processed in local bits and pieces, but rather are subject to a massively parallel reduction that leads to a number of important computational achievements. Parallelism in motion analysis allows animals to steer themselves, it permits the acquisition of depth information from motion parallax, it supports motion camouflage breaking, and it makes the tracking of moving objects a fairly effortless exercise in most circumstances. The mammalian visual system is evidently exquisitely attuned to motion and this observation has naturally led to more general inquiries into the logic of motion analysis, its realization in neural tissue, and to more complete inventories of the psychophysics of detection and discrimination of motion fields (e.g., Blake & Aiba, 1998; Freeman & Harris, 1992; Harris, Morgan, & Still, 1981; Morrone, Burr, & Vaina, 1995; Nakayama, Silverman, Macleod, & Mulligan, 1985; Regan & Beverly, 1978; Sekuler, 1992; Watamaniuk & Sekuler, 1992; Werkhoven & Koenderink, 1991).

One of the first pieces of evidence that motion sensing might not always

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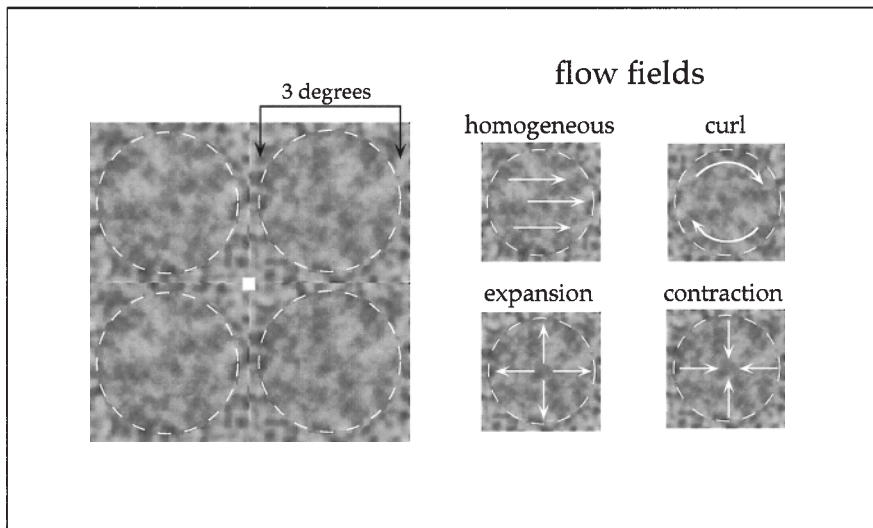
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proceed in a parallel fashion concerned the segmentation of motion fields by rotation sign (Julesz & Hesse, 1970). In these experiments observers viewed ensembles of rotating needles that were divided into two regions on the basis of sign, counterclockwise or clockwise. Although the regions were well marked out and had simple boundaries, these boundaries were quite difficult to discern and there was no grouping on the basis of the sign. It is simply not possible to gain a collective percept of a common direction of rotation when the individual elements are independently distributed in space. The implication is that direction differences among rotating elements are not processed in parallel. These results are in clear contrast with what is observed when the needles are replaced by patches of drifting texture. Ensembles of local patches of drifting texture segment effortlessly on the basis of sign. Not only are region boundaries quite salient, but the regions of common sign separate into distinct depth planes. The percept of depth is, of course, a consequence of motion parallax, but the point is clear; the direction of drifting texture is processed in parallel. This conclusion has been substantiated by the lack of set size effects in standard visual search (Nakayama & Silverman, 1986).

Theories of attention are not sufficiently well developed to provide a fundamental explanation for why rotation direction and translation direction occupy different categories of attentional process. However, the methods of attentional assessment we employ are sufficiently powerful to address the simpler question of what level of motion description is appropriate for describing the different ways attention is allocated. In this article we consider two distinct levels of motion representation: an *image-based* level of representation governed by distinctions in optic flow and a *scene-based* level of representation governed by distinctions in distal object motion. An empirical analysis can decide which scheme matches the attentional limitations that are actually observed during direction discrimination. If attention operates solely on image-based representations of motion, then direction discrimination will be limited by the literal structure of the optic flow field (i.e., whether one dynamic pattern of light can be efficiently distinguished from another dynamic pattern of light). On the other hand, if attention has access to scene-based representations, then direction discrimination may be based instead on perceptions about what objects are doing distally (i.e., whether one type of displacement can be distinguished from another displacement). Once we know what level of description is relevant for describing attentional bottlenecks, we will be able to attack the more difficult questions concerning why certain motions and not others permit efficient and parallel direction acquisition. We begin with a discussion of the geometric character of optic flow fields and a review of what is known about the neural processes that accomplish direction selectivity.

In physical or environmental terms, rigid objects execute only two kinds of motion—translations and rotations. There are, however, a number of basic



**FIG. 1.** Stimulus configuration and types of flow fields examined in the multiple target search paradigm. Target and distractor motion directions appeared in at least one of four circular regions and empty regions were filled with dynamic random noise. White lines are included to indicate motion flow and boundary and were not present in the actual displays. The flow fields on the right include arrows representing target direction for each motion condition.

types of optic flow that are induced by the projections of these motions on the retina. These flows are defined by the differential structure of their associated vector fields and are crudely represented in Fig. 1. Homogeneous flow is produced by translation in the fronto-parallel picture plane (e.g., a right-to-left displacement), curl flow is produced by rotations about the line of sight (clockwise or counterclockwise displacement within the picture plane), and divergence flow is produced by translations along the line of sight and is characterized by the inflow (contraction) or outflow (expansion) of texture from a vanishing point.<sup>1</sup> Homogeneous flow is unique by virtue of its infor-

<sup>1</sup> Both *curl* and *divergence* arise in the vector analysis of the optic flow field  $\mathbf{F}$  through the application of the differential operator

$$\nabla = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j} + \frac{\partial}{\partial z} \mathbf{k}.$$

Note that bold symbols denote vector quantities. The operation  $\nabla \cdot \mathbf{F}$  yields a measure of *divergence* at each point in the flow field (i.e., the dot product of  $\nabla$  and  $\mathbf{F}$ , a measure roughly corresponding to the rate of flow radiating in or out of a small region of space), whereas  $\nabla \times \mathbf{F}$  yields a measure of *curl* at each point in the flow field (i.e., the cross product of  $\nabla$  and  $\mathbf{F}$ , a measure roughly corresponding to the rate of flow circulation about a small region of space). The optic flow field  $\mathbf{F}_t$  induced solely by projection of translating object texture has, by definition, constant velocity at every point, and subsequently both  $\nabla \cdot \mathbf{F}_t$  and  $\nabla \times \mathbf{F}_t$  vanish

mational redundancy; direction analysis at any point suffices to specify the direction of the entire field. In contrast, the other types of optic flow have position dependent directions that are arranged about a point or line. Expansions are distinguished from contractions, for example, not by velocity differences at a single point, but by how the flow is globally arranged. From here on we denote both divergence (expanding/contracting) and curl (rotational) as *complex* in light of the fact that these types of flow require representations of spatial layout, whereas the class of *simple* homogeneous flows does not.

The distinction in geometry between simple and complex flow motivates one of the major questions posed by this article: Does the representation of spatial information required for computation of direction determine how attention gets allocated? There is a large body of evidence suggesting that discriminations based on the relative position of "features" require effortful and focused attention (Enns & Rensink, 1990; Logan, 1994; Moore, Egeth, Berglan, & Luck, 1996; Palmer, 1994; Poder, 1999; Saarinen, 1996; Thornton & Gilden, 2000; Wolfe & Bennett, 1996; but see Heathcote & Mewhort, 1993). These findings are relevant here because complex flow direction can be cast in terms of the relative positions of local motion vectors (see Sekuler, 1992; Takeuchi, 1997). For example, both clockwise and counterclockwise rotation have leftward and rightward moving components—what uniquely distinguishes clockwise motion is that its rightward component is organized *above* its leftward component. Again, it is the need for relations like "above" that make descriptions of curl and divergence flow more elaborate than descriptions of homogeneous flow. If complex flow direction is represented through particular conjunctions of local motion "features," we should expect its discrimination to be an attentionally intensive undertaking. There are several lines of psychophysical evidence which support this view. Using rotary-based textures, Julesz and Hesse (1970) provided strong evidence that the sensing of curl sign is attentionally demanding—there was little to no segmentation of regions containing clockwise motion from regions containing counterclockwise motion. Braddick and Holliday (1991) extended these limitations to the sensing of divergence sign. Using a standard visual search methodology they showed that response times to find an ex-

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everywhere implying an irrotational field with zero divergence. It is in this sense that we denote  $F_1$  as a *homogeneous* flow field (for a review see Koenderink, 1986).

In addition to homogeneous, divergence, and curl, there is one other basic class of optic flow we have not mentioned. Deformation flow is produced by rotations in depth and is characterized by inflow along one axis and outflow along an orthogonal axis. In this work we have chosen to focus exclusively on homogeneous, divergence, and curl flow fields and will not examine the attentional limitations that attend the analysis of pure deformation flow. There are two major reasons which support such an omission: First, there is a considerable legacy of work in the psychophysics providing a comparative analysis of translation, expansion/contraction, and rotational motions; second, at present there appears to be little physiological or psychophysical evidence for explicit mechanisms analyzing deformation flow.

panding “target” among contracting distractors rose sharply as the number of distractors increased, a pattern generally thought to signal a serial or highly capacity-limited search (see Takeuchi, 1997, for an opposed finding). These results suggest that textures made from local patches of divergence flow would not segment on the basis of direction, and such is the case (Gilden & Kaiser, 1992).<sup>2</sup>

The geometric distinction we have drawn between *simple* and *complex* optic flow is reiterated in the physiology of motion sensing. Local translational motion is analyzed in visual cortex via neurons that act as spatiotemporal filters (Adelson & Bergen, 1985; Reichardt, 1957; van Santen & Sperling, 1984; Watson & Ahumada, 1985). These filters are commonly referred to as Reichardt detectors and are tuned only to spatial displacement over time. They cannot represent direction in curl or divergence flows because they lack the power to define axes of rotation or vanishing points. Filters that *can* define curl and divergence direction require a representation of spatial layout. Although neuroanatomical understandings of such filters are crude, mechanisms that sense *complex* flow (rotation and expansion/contraction) are conceived to do so by spatial integrations over appropriate configurations of Reichardt units (Morrone et al., 1995; Saito, Yukie, Tanaka, Hikosaka, Fukada, & Iwai, 1986; Simoncelli & Heeger, 1998; Tanaka, Fukada, & Saito, 1989).

There are additional aspects of neural motion sensing that support the division of homogeneous flow from curl and divergence flows. In the earliest levels of striate cortex, neurons are selective only for local translations within the frontal plane (see Movshon, Adelson, Gizzi, & Newsome, 1985, for a review). It is not until reaching extrastriate areas MT and MSTd that neurons selective for divergence or curl flow begin to show up in the single cell demographics (Tanaka et al., 1989; Tanaka & Saito, 1989); though even at these levels in the motion processing hierarchy there still remain more cells selective for homogeneous flow than for complex flow (Saito et al., 1986; Tanaka & Saito, 1989). Evidence of neural linking between divergence and curl flow has also been found in cells uniquely tuned to spiral motions (Graziano, Anderson, & Snowden, 1994; for psychophysical evidence see Snowden & Milne, 1996). This finding suggests that divergence and curl flows may in fact be neurally represented as special cases in the more general class of spiral motion (but see Burr, Ross, & Badcock, 2000).

Despite the apparent coherence of the physiology and the psychophysics, the empirical foundations are not solid. First, most of the relevant studies that have treated motion sign have characterized processing quality using

<sup>2</sup> We have conducted many informal observations of textures whose regions differ only in motion sign. For both divergence and curl textures, sign-based segmentation is virtually absent and qualitatively different from the strong segmentation percepts produced by homogeneous textures.

the theoretically weak paradigm of *singleton* visual search (Braddick & Holliday, 1991; Takeuchi, 1997). This method of search, though a favorite among attention researchers, is flawed in a number of ways that undermine a clear assessment of attentional limitation (Carrasco & Yeshurun, 1998; Palmer, 1994; Townsend, 1990). Second, recent psychophysical work has raised questions about the nature of processing during discrimination of divergence direction. Using a set of motion stimuli superior to those used in earlier assessments, Takeuchi (1997) found little evidence of capacity limitation during search for an expanding target among contracting distractors. This result runs counter to the study by Braddick and Holliday (1991), and is an isolated piece of evidence suggesting that attention may respect scene-based representations of motion. Finally, straightforward links between motion physiology and perception have been slow in coming; we still do not have a complete understanding of neural circuits and consequently the implication of single cell recordings is unclear.

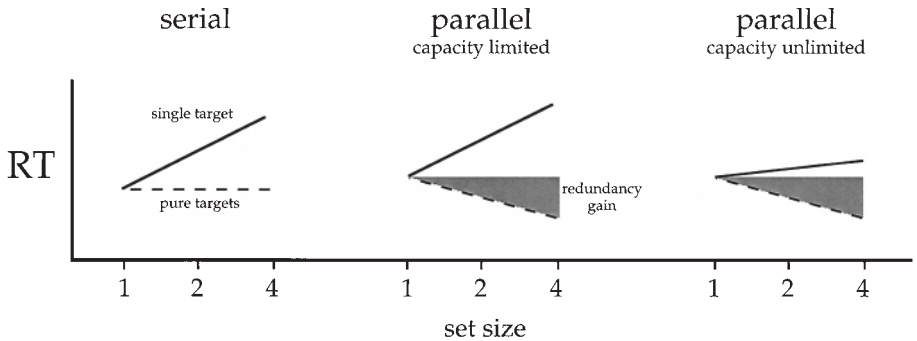
While divergence and curl flow fields appear to be naturally associated in terms of computation and physiology, it must be remembered that distally, the motion that induces divergence flow is a pure translation that just happens to be along the observer's line of sight (movement toward or away from the observer). In terms of distal object motion, it is homogenous and divergence flows that are associated because they have a common *etiology* (i.e., translational displacement). For this reason divergence flow is key to inferring the level of representation used by attention in acquiring the information that specifies direction. Specifically, if it is the case that attention uses image-based representations bound to the line of sight, then the acquisition of direction in divergence flow fields should be similar to curl, i.e., serial-like or highly capacity limited. However, if attention uses scene-based representations that are invariant over the line of sight, then direction analysis in divergence flow fields should be similar to homogeneous flow, i.e., parallel with little capacity limitation.

In this work we reexamine the attentional constraints of direction perception using two independent paradigms that have the power to distinguish between types of attentional load. Furthermore, we systematically investigate a set of flows that is sufficient to determine whether attentional allocation is guided by image-based or scene-based descriptions of motion. The first paradigm employs multiple target search and is specifically designed to reveal spatial parallelism in the presence of inefficient, capacity limited processing (Snodgrass & Townsend, 1980; Townsend, 1990; van der Heijden, La Heij, & Boer, 1983). The second paradigm makes the same distinctions in terms of serial correlations in accuracy during signal detection (Gilden & Wilson, 1995). By incorporating a set of converging operations into our inquiry we hope to generate a consistent principle governing the logic of attention, recognizing that any given method may rest on questionable assumptions (Garner, Hake, & Eriksen, 1956).

### *Multiple-Target Search*

Excluding early work in texture segmentation, most previous research examining perceptual acquisition of motion sign has relied exclusively on singleton search (Braddick & Holliday, 1991; Takeuchi, 1997). This method represents the workhorse of the attention field and consists of the speeded discrimination of displays containing a *single* target element hidden among  $n$  distractor elements from displays containing only distractor elements. Response time (RT) to signal target presence is measured as a function of distractor number (set size), and the rate at which RT increases with set size is used to categorize search as either *serial* or *parallel* in nature (for a comprehensive review, see Wolfe, 1998b). Despite the empirical and theoretical simplicity of the approach, standard visual search is known to have serious methodological flaws given its inability to distinguish serial processes from parallel processes that are limited in capacity—both types of processes are capable of producing linear increases in RT with set size (Townsend, 1972, 1974; Wolfe, 1998a). Further, a clear interpretation of the usage of attentional resources based solely on RT by set size slopes is difficult given that low-level eccentricity and density effects are often confounded with set size (Carrasco & Yeshurun, 1998; Duncan & Humphreys, 1989; Geisler & Chou, 1995; Palmer, 1995; Palmer, Ames, & Lindsey, 1993). To circumvent such shortcomings we use a hybrid search paradigm. Like standard visual search methods, this composite paradigm focuses on variation in RT as set size is manipulated over trials. However, unlike previous methods, this paradigm is equipped to distinguish between various types of resource allocation by its inclusion of a redundant–target condition (Biederman & Checkosky, 1970; Snodgrass & Townsend, 1980; van der Heijden, La Heij, & Boer, 1983). Specifically, multiple target trials are randomly interleaved with the single and no-target trials familiar to singleton search designs while subjects make speeded decisions as to the presence or absence of a target. Decreasing RT with increasing target number is evidence of parallelism, most notably for the case in which only targets occur in a display and comparisons are made across target number (Townsend, 1990). We denote trials in which a display contains only target elements as “pure” target trials. These trials are central to our design because they alone unambiguously signal the serial or parallel nature of search. A comparison of pure–target conditions is diagnostic in this regard precisely because there is no need to search a display containing only targets. A serial search predicts that pure–target RTs will be invariant across target number. In contrast, when search is parallel in nature the prediction is that RT should decrease with target number, owing either to statistical considerations (“race gains”) or spatial pooling (see Miller, 1982).

In Fig. 2 we show predicted single and pure–target RTs for three different models of search processing. The leftmost panel represents the predicted pattern of RTs when search is based on a *serial* process; the center panel



**FIG. 2.** Patterns of predicted RT using the multiple-target search method. The lines marked “single target” refer to trials in which only a single target is displayed among a variable number of distractor elements. The lines marked “pure targets” refer to trials in which displays contain only targets. These pure-target trials are central to the multiple-target method because they have the power to distinguish *serial* processes from those that are *parallel* and of limited capacity. The gray, triangular regions shown in the center and right panels of the figure denote redundancy gains (i.e., faster target “present” RT as target number increases), a pattern of pure-target responding uniquely associated with *parallel* search. Whenever there are reliable redundancy gains in the pure-target conditions, *serial* processing can be effectively ruled out.

represents the predicted pattern of RTs when search is based on a *parallel, limited capacity* process; and the right panel represents the predicted pattern of RTs when search is *parallel, unlimited capacity*. In each panel the solid lines marked “single target” denote hypothetical RTs for trials in which a single target is present among a variable number of distractors (set size increases from left to right). The dashed lines marked “pure targets” denote RTs for trials in which only targets appear in a display (increases in set size here correspond to increases in target numerosity). The figure highlights the shortcomings inherent in the use of “single target” data—there simply is not enough structure available to discriminate *serial* processes from those that are *parallel* and of limited capacity. Figure 2 clearly shows that this distinction can only be made by considering the pure-target response times; whenever there are decreases in response time with pure-target number (i.e., redundancy gains), *serial* models of search can be effectively ruled out in favor of spatial parallelism.

Though redundant target manipulations are not new, the work reported here represents one of the first attempts to incorporate these manipulations into a standard search methodology. Much of the previous work that has used similar manipulations has been primarily interested in the mechanism(s) by which target redundancy improves performance (Diederich & Colonius, 1991; Egeth, Folk, & Mullin, 1988; Fournier & Eriksen, 1990; Miller, 1982; Mordkoff, Miller, & Roch, 1996; Mordkoff & Yantis, 1991; Schwarz, 1994; Townsend & Nozawa, 1995, 1997). Generally, the focus has been on using



estimates of the single and double target RT cumulatives to distinguish whether redundancy gains arise from *statistical facilitation* (Rabb, 1962) or from *coactivation* of sensory channels (Miller, 1982, 1986, 1991). Because the basic focus has been on the etiology of the redundancy gain itself, much of the previous research has used simple target detection tasks, has fixed set size to be no more than two, and has designated targets arbitrarily (for example, a tone and a simple visual marker may both be “targets” in a single experiment). The redundant target method used here employs a set of different techniques. First, because we are primarily interested in capacity limitation, we investigate discrimination performance as a function of set size. Second, our methodology defines a target as a single unique thing—when displays contain more than one target they always contain multiple repetitions of this one thing (Egeth & Mordkoff, 1991; Mordkoff, Yantis, & Egeth, 1990; van der Heijden et al., 1983). Finally, we remain neutral concerning *how* redundancy gains arise and are solely concerned with characterizing the circumstances under which they are observed.

#### *Correlated outcomes in signal detection*

Our second methodology uses an altogether different approach for assessing allocation of attentional resources. With this method we replace the analysis of average RT that forms the basis of traditional search methods with an analysis of performance fluctuations during repeated discrimination. Specifically, we examine the statistics of trial-to-trial accuracy for a single motion stimulus fixed at threshold. By measuring the degree to which outcomes (being correct or incorrect) acquire temporal correlations during direction discrimination, we gain insight into the underlying attentional constraints that limit the acquisition of motion sign. Though this type of technique is relatively novel, it promises to be a potentially powerful means of distinguishing attentive from preattentive processing and has preliminary empirical support (Gilden & Wilson, 1995).

This method capitalizes on the observation that correct responses tend to cluster in time when discriminations are made near threshold (Gilden & Wilson, 1995). Outcome clustering is informally termed “streakiness” when there is a positive sequential dependency across a trial sequence such that correct judgments tend to follow correct judgments. One of the principle findings of Gilden and Wilson (1995) was that all preattentive discriminations generated an equivalent and extreme magnitude of correctness clustering as measured by the runs  $z$  score (negative runs  $z$  scores indicate clustering; positive runs  $z$  scores indicate greater outcome alternation than expected by chance, see streak analysis later). In every case, preattentive discriminations produced an average runs  $z$  score of  $-1$ . A variety of attentionally demanding discriminations were also assessed and it was found that these neatly dissociated from their preattentive counterparts, producing clustering much more consistent with Bernoulli expectation (i.e., a runs  $z$  score closer

to 0). In sum, the empirical situation provided by the work of Gilden and Wilson (1995) is consistent and straightforward: Sequences from attentionally demanding tasks are not very streaky, although they can be distinguished from those produced by a Bernoulli process; sequences associated with preattentive discrimination are all of one kind and are maximally streaky. We propose to use this simple tool to distinguish varieties of attentional load on the basis of fluctuations in discrimination accuracy.

The theoretical basis for streak formation was discussed thoroughly in Gilden and Wilson (1995) and Gilden (2001). The problem addressed in both articles was what aspect of performance leads to positive sequential dependencies where hits segregate from misses. Gilden and Wilson (1995) used Monte Carlo simulations to show that learning, intermittency in effort, and simple forms of conditionalization (success breeds success) cannot describe the sequence structure produced by people engaged in repeated discriminations. In Gilden (2001) streak formation was shown to be part of a much broader phenomenon involving the production of  $1/f$  noise (see Gilden, 1997; Gilden, Thornton, & Mallon, 1995). This unification implies that the ontogeny of streaks is a real problem and not one that is going to be explained away with facile arguments;  $1/f$  noises are often observed in the temporal fluctuations of complex systems and their etiology is one of the main unsolved problems in statistical mechanics.

In this article we are not as concerned with the existence of streaks as we are with the observation that attentional demand predicts the level of intertrial correlation. The linkage between streaks and attention has to be understood in terms of the temporal dynamics that produce  $1/f$  noises:  $1/f$  noises are theorized to be natural outcomes in systems that are able to self-organize and reach critical states (Bak & Chen, 1991; Bak, Chen, & Creutz, 1989; Bak, Tang, & Wiesenfeld, 1987). In this way we are led to consider how attention could modify the dynamics of a self-organizing critical system. Gilden (2001) gave evidence that  $1/f$  fluctuations arise as a consequence of an internal dynamic involved in the formation of representations. Attention appears to operate relatively independently of this dynamic and acts rather as a source of disruptive perturbation. The empirical data indicate that the level of perturbation is monotonically related to the magnitude of attentional demand (Gilden & Wilson, 1995). Perturbations act on the system to drive it away from the critical state where it can emit  $1/f$  noises and so cause the entire process to decorrelate in time. Where attentional usage is minimal, say as for luminance or orientation discrimination, an unperturbed view of the critical state can be measured. The unperturbed view is the situation where runs  $z$  scores are  $-1$ , and it is for this reason that preattentive discriminations form an equivalence class in hit clustering.

We want to emphasize here that the theory and empirical work linking attention to outcome clustering, though somewhat novel, is not at odds with any of the existing psychophysics. While the theory holds that attentive pro-

cessing disrupts an endogenous source of correlated noise, it is entirely neutral regarding how attention affects the overall signal-to-noise ratio. This relation has been thoroughly investigated elsewhere and continues to fuel an active debate regarding how attention influences discrimination performance in the *mean*; that is, how it influences psychometric functions and filter bandwidths (Doshier & Lu, 2000; Lu & Doshier, 1998; McAdams & Maunsell, 1999; Prinzmetal & Wilson, 1997; Treue & Maunsell, 1999). The method we use here has no relation to any of these issues insofar as all our conditions generate roughly equivalent psychometric functions (see Streak methods). We are only concerned with temporal correlation; the way that hits and misses are distributed over time.

Streak analysis has several advantages over texture and search methodologies, which likewise attempt to distinguish preattention from focused attention. First, the streak paradigm places all stimulus discriminations near threshold and in so doing minimizes stimulus differences across tasks, a confound which has undermined the clear analysis of singleton slopes across typical visual search experiments (Duncan & Humphreys, 1989; Palmer, Ames, & Lindsey, 1993; Wolfe, 1998a). Second, low-level confounds such as eccentricity and density effects are eliminated because only a single stimulus is presented at fixation. Finally, the analysis and interpretation of outcome clustering requires none of the variance or distributional assumptions of standard signal detection theory, nor does it mandate any additional theory regarding how information is accumulated toward decision. To import this technique into the motion domain we fix direction discrimination at threshold levels of performance and examine the degree of streakiness that results across a block of trials. It is then simply a matter of comparing observed levels of streakiness to baseline measures obtained for tasks known to be preattentive.<sup>3</sup> This comparison is possible precisely because we are able to interpret specific points along the runs  $z$  score continuum. Following Gilden and Wilson (1995), we now know that there are two regimes of streakiness: (1) discriminations that are minimally demanding of attentional resources yield average runs  $z$  scores that are shifted 1 standard deviation below Bernoulli expectation (i.e., mean  $z = -1$ ) and (2) discriminations that suffer high capacity limitations yield runs  $z$  scores that are significantly less streaky,

<sup>3</sup> Though evidence has begun to emerge to question whether any discrimination can truly be called "preattentive" (e.g., Joseph, Chun, & Nakayama, 1997), we have chosen to retain the term *preattentive* in this article as a means of nominally categorizing the set of psychologically simple discriminations for which stimulus differences (or similarities) are available in parallel, with little to no capacity limitation. Such *preattentive* discriminations impose minimal costs on search time as distracting information is increased and support effortless texture segmentation. This denotation is not meant to imply a strict absence of attention, but rather that the attentional requirements are qualitatively distinct from those stimulus discriminations requiring focused attention (i.e., discriminations that yield large costs in RT with increases in distraction and do not support effortless texture segmentation).

with an average  $z$  near  $-.3$ . The importance of  $z = -1$  bears repeating; in this theory it is the value that anchors the attention-clustering mapping by defining a lower bound of attentional usage.

A crucial step in validating the integrity of our method is to insure that preattentive discrimination of motion sign does produce an average runs  $z$  of  $-1$ . Discrimination of the sign of homogeneous flow is the appropriate benchmark in this context because it is a paradigmatic example of a preattentive discrimination—there would be no depth from motion parallax were it not for this perceptual fluency. If we find that this discrimination fails to meet the point prediction set by preattention (i.e., average runs  $z = -1$ ), the interpretation of all other results becomes problematic.

## METHODS

### *Multiple-Target Search*

In our first experiment a total of 36 naive participants searched for a “target” direction in one of four basic flow conditions with 9 participants each assigned randomly to either homogeneous, expansion, contraction, or curl conditions. For the homogeneous and curl conditions participants searched for rightward, translational motion, or clockwise rotary motion, while for divergence flow we examined search for both expanding and contracting targets in separate experiments. This choice was motivated in part by previous findings of an anisotropy between expanding and contracting motion in the physiology and psychophysics (Ball & Sekuler, 1980; Edwards & Badcock, 1993; Graziano et al., 1994; Harris et al., 1981; Reinhardt-Rutland, 1994; Takeuchi, 1997).

Participants in each condition viewed a variable number of animated noise textures that either translated unidirectionally within the frontal plane (left/right), translated along the line of sight in motion orthogonal to the frontal plane (expansion/contraction), or rotated within the plane (clockwise/counterclockwise). Individual animations consisted of sequences of random texture that were constructed to have the same power spectra as natural landscapes (Burrough, 1981; Keller, Crownover, & Chen, 1987; Sayles & Thomas, 1978; van der Schaaf & van Hateren, 1996; Voss, 1988). Single frames for each animation were created by repeatedly applying a motion transformation to an underlying field of randomly colored black and white dots (density was maximal in that every pixel participated in the motion transformations; individual dots subtended  $\sim 2$  arc min). For translational motion, dots were shifted to the left or right across frames; for expanding/contracting motion, dots were displaced radially toward or away from the center of each frame; for rotary motion, each dot was displaced along a virtual circle, such that its distance from the center of the frame remained constant across frames. For the expanding/contracting and rotary displays, local dot velocities were proportional to radial distance so as to maintain realistic, solid body motion. After creating a sequence of moving black/white dot fields, each frame in the sequence was spatially smoothed to produce the cloudlike structures seen in Fig. 1. This was done by convolving a 2D exponential weighting function with the underlying black/white dot fields (essentially, the decay rate of the exponential weighting function was chosen so as to exclude pixels falling outside a  $6 \times 6$ -pixel neighborhood). All animations supported the percept of continuous motion and were presented until response against a matched background of uncorrelated dynamic noise. The phenomenal experience of these animations was that of coherent motion occurring within apertures defined by a noisy surround. Single frames from example stimuli are shown in Fig. 1. All stimuli were equated across motion type for spatial extent ( $3^\circ$  visual angle), contrast,

spatial frequency content, and average dot speed ( $\sim 1.5^\circ/\text{s}$ ). Viewing distance was fixed at approximately 57 cm by means of a chin rest.

For multiple element search, any given trial contained one, two, or four moving noise textures that appeared within circular apertures configured symmetrically about a central fixation point. The number of trials for each set size was balanced, and across set size, animations containing at least one target motion direction occurred as frequently as those containing no target motion direction. In pure-target conditions all apertures contained the target motion direction (i.e., number of targets = set size) and the number of trials was balanced across target number within each set size. The remaining trials contained all possible permutations of target and nontarget mixtures, and in all cases empty apertures were replaced with filtered background noise. In this experiment a participant's task was simply to make speeded "yes"/"no" decisions as to whether at least one target direction was present while maintaining accuracy above 90%. Each participant received a block of 288 practice trials before completing two additional blocks for a total of 576 trials. Prior to analysis we excluded all trials on which errors had occurred ( $<10\%$  of the data), and then computed both within-subject medians and standard errors for all conditions.

In any assessment of visual attention, care must be taken to distinguish attentional limitations from simply being unable to see the stimulus elements due to loss of resolution off the fovea. We verified that the direction of individual homogeneous and curl stimulus fields were equally discriminable at all eccentricities using an approach similar to Geisler and Chou (1995). By reducing contrast and presentation time, we measured accuracy using single interval sign discrimination to obtain psychometric functions as a function of stimulus eccentricity. Performance for single element homogeneous and curl displays was identical over the limits of our viewing apparatus (i.e., up to an eccentricity of  $25^\circ$  of visual angle). Performance parity across motion type in terms of single element detection/discrimination has support from a number of psychophysical studies (see Ahlstrom & Borjesson, 1996; Bell & Lappin, 1979; Blake & Aiba, 1998; Morrone et al., 1995; Werkhoven & Koenderink, 1991).

### *Streak Formation in Signal Detection*

In our second experiment, five practiced observers made repeated discriminations of direction for homogeneous flow (left/right translation), divergence flow (expanding/contracting motion), and curl flow (clockwise/counterclockwise rotation). All three flow conditions were administered to each participant in an order that was counterbalanced.

The streak methodology requires that discrimination occur near threshold; where there are no errors there are no streaks. In order to achieve threshold levels of performance we constructed random dot displays that differ in two principle ways from those described in the search methods. First, the stimuli used here have inherently weaker motion signals because only a subset of the dots moves coherently from frame to frame (the remaining "noise" dots are randomly relocated across frames). In contrast, the dot displays used in our search experiment are 100% coherent because every dot participates in the motion signal. Second, the random dot fields used in this experiment are not spatially filtered. The primary reason for this is that there is a distinction between filtering a coherent signal and filtering a largely incoherent signal. Filtering a fully coherent input signal leads to a fully coherent output signal (i.e., a naturalistic motion texture); filtering a largely incoherent input leads to an output that is difficult to characterize and, moreover, difficult to control. We chose to use unfiltered, random dot fields because they can be exactly specified and have a long history in the study of threshold level motion phenomena (Bell & Lappin, 1979; Gilden, Hiris, & Blake, 1995; Morrone et al., 1995; Snowden & Milne, 1996; Watamaniuk & Sekuler, 1992; Williams & Sekuler, 1984).

On each trial a single, black/white random dot field appeared within a circular aperture presented at fixation (subtending  $3^\circ$  visual angle at a distance of 57 cm). A motion signal was created by constraining a small percentage of the total number of dots in each display to move

coherently in one of two chosen directions amid remaining noise dots that were replaced randomly from frame to frame (dot size was  $\sim 2$  arc min; dot density was maximal). The percentage of coherent dots was chosen individually for each observer to maintain an average accuracy of about 75%. Thresholds were estimated using the method of constant stimuli. Through maximum likelihood fits of a generalized Weibull function it was verified that the psychometric functions were similar across motion type [average 75% threshold (percentage of coherent dots): 3.2 for homogeneous, 3.8 for curl; average slope of psychometric: 1.223 for homogeneous, 1.227 for curl]. For divergence direction discrimination, instead of computing psychometric functions we achieved similar levels of performance (around 75%) by choosing an appropriate coherence level for each observer from a fixed set of premade animation ensembles (average percentage of coherent dots chosen across observer was 2.4).

Average speed and dot displacement were equated across the three motion conditions. In this single interval discrimination task, each trial consisted of an 800-ms presentation followed by a response. The probability of encountering any particular motion direction was balanced over trials and stimulus ordering was randomized for each run. A block of trials consisted of 240 discriminations of a single type of motion at a fixed percentage of coherent dots. Trial presentation was continuous and fast paced and no feedback was given. Each observer provided eight blocks of data in each motion condition.

### *Streak Analysis*

Each individual sequence of 240 successive discriminations was analyzed in terms of trial-to-trial outcome (correct or incorrect). Outcome clustering was measured by counting the number of runs in a given sequence, where a run is defined as a subsequence of like outcomes. For example, consider the following binary-valued sequence in which correct and incorrect decisions are represented as "1"s or "0"s as follows: 1 1 1 0 0 0 1 0 0 1. This sequence of hypothetical outcomes has exactly five runs (111, 000, 1, 00, 1) and a hit rate of 50%. Once we know the hit rate and run count of a sequence, the probability of obtaining that number of runs or fewer can be computed under the null hypothesis that trial outcomes are the result of a stationary Bernoulli process. This probability is then converted to a runs  $z$  score by inverting a standard Gaussian cumulative. As a statistic the runs  $z$  score is virtually identical to the Fisher  $z$  of the serial correlation and quantifies departure from trial independence.<sup>4</sup> Specifically, a negative runs  $z$  score implies that there are *fewer* runs in a sequence than expected for a given hit rate. Negative runs  $z$  scores indicate outcome clustering in which correct decisions tend to segregate from incorrect decisions. In contrast, when there is a positive runs  $z$  score there are *more* runs in a sequence than expected. Positive runs  $z$  scores are associated with discrimination sequences in which correct decisions tend to alternate with incorrect decisions. The magnitude of outcome clustering for each motion type was computed simply by forming the average runs  $z$  score.

## RESULTS

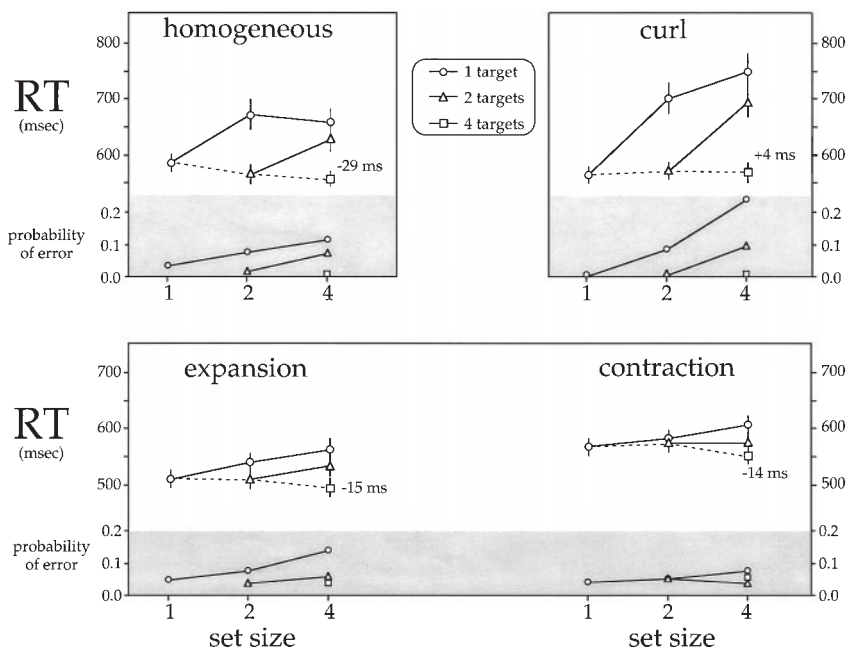
The inductive power of the method of converging operations derives from the independence of the various assessment tools. In this regard, the methods we have used to characterize resource allocation are optimal: They have

<sup>4</sup> There exist a number of different statistics that effectively capture sequence nonstationarity, and the associated advantages and disadvantages of these various measures have been discussed in detail elsewhere (Gilden & Wilson, 1995; Gilden, 2001). In short, we have opted to use the runs  $z$  statistic in these analyses because it necessarily factors out contributions of overall sequence hit rate to within-sequence "streakiness."

virtually nothing in common. The search method employs suprathreshold stimuli and an analysis based on traditional cell means in which the residuals do not enter into the theory. The streak paradigm employs threshold-level stimuli and an analysis based solely on fluctuating quantities in which the cell means (hit rates) are irrelevant. Any convergence in interpretation that may result from the application of two such highly independent methods is unlikely to be a fortuity.

### Multiple-Target Search

Average median reaction times and error rates for direction search are shown in Fig. 3. Results are plotted for each target/distractor combination as a function of set size for homogeneous flow, curl flow, and both diver-



**FIG. 3.** Results of the multiple-target search experiment. Means of median response times for correct trials are plotted with average within-participant standard errors. Points connected by solid lines represent trials in which target number was fixed across variation in set size. Open circles denote means for trials in which a singleton target was presented among zero, one, or three distractors depending on set size. Open triangles denote means for trials in which two targets were presented among zero or two distractors. Open squares denote means for trials in which all four elements presented were targets. Points connected by dashed lines indicate means for pure-four-target trials in which all presented elements were targets. Redundancy gains in milliseconds ( $RT_{4\text{ targets}} - RT_{1\text{ target}}$ ) are inset for each flow type. The corresponding error rates averaged over participants are plotted below the response time functions.

gence flow conditions.<sup>5</sup> Within each graph points lying on the same solid line represent those conditions in which distractor number varied while target number was fixed. The dashed lines within each graph signify average RTs for trials in which every presented element underwent target motion. Recall that for these so called pure–target trials, increases in set size are also increases in target redundancy.

The results for trials connected by solid lines show a similar pattern across all four direction searches in so far as target “present” responses were slower on average with increases in distractor number. We have estimated the rate at which single target RT increases with set size for each observer in each condition using standard regression techniques. Both homogeneous and divergence flow conditions have average RT by set size functions much shallower than that found for curl (homogeneous: 20 ms/item; expansion: 16 ms/item; contraction: 13 ms/item; curl: 56 ms/item). Positive increments in response time as a function of set size suggest capacity limitation, and it is evident from the figure that (a) these limitations appear to be present for all flow conditions and (b) they are much greater in the case of the curl condition.

Single target functions in the context of redundant target search are generally not diagnostic of processing style because all discriminations, including those based on variation along a single feature dimension (e.g., orientation, color), yield nontrivial increases in RT with set size (Thornton & Gilden, 2000). There are three reasons why even “pop-out” discriminations may show some set size effects in the context of this method. First, search performance is typically not measured at a set size of one. It may be that this condition is qualitatively different from larger set sizes by virtue of the fact that there is no need to “search” a display containing a single element. Second, in order to deconfound attentional and eccentricity effects, we use a redundant target method that limits set size to no more than four elements. The majority of previous search experiments have included large set sizes that may in fact improve discriminability by increasing local target/distractor contrast (Nothdurft, 1985; Rubenstein & Sagi, 1990). Finally, there are recent proofs that a parallel, unlimited capacity search model can yield modest set size effects when error rates are held constant across set size (see Palmer & McLean, 1995).

Although all of the one-target functions have positive slopes and are there-

<sup>5</sup> Reaction times in target absent conditions are generally not included in demonstrations of attentional process because they are known to be corrupted by various termination strategies (Wolfe, 1998b). We have accounted for our target absent conditions using a modified random walk model and find that response criteria are relaxed monotonically as set size increases (Thornton & Gilden, 2000). Other than this relatively obscure effect, the target absent data do not speak to the issue of resource allocation.



fore “serial-like” (in the sense motivated by feature integration theory; Treisman & Gelade, 1980), the curl slopes are significantly larger than those in the homogeneous and divergence conditions (all  $ps < .0001$  using Fisher’s PLSD). This is the first piece of evidence that curl search is unique in its usage of attentional resources. The real power of this method, though, derives from the analysis of the pure–target trials and it is here that we find more conclusive evidence that in the analysis of flow direction, only curl search has all of the features of a truly “serial-like” process.

Consider then the pure–target response times; those points connected by dashed lines in Fig. 3. When search is for a homogeneous, expanding, or contracting target, increases in target redundancy lead to *faster* target “present” response times, and these benefits in responding provide strong evidence of spatial parallelism (see favored positions analysis below). For homogeneous flow there is a significant response benefit of 29 ms when pure–target number is increased from one to four [ $F(1, 16) = 8.1, p = .006$ ]. Despite a slight offset in terms of absolute reaction time, both divergence searches produced nearly identical gains under target redundancy, and in general the entire pattern of median RTs was remarkably similar for both expanding and contracting targets. For both divergence flow directions there was a moderate benefit of approximately 15 ms for four targets relative to one target. Our failure to find a search asymmetry between expanding and contracting targets is inconsistent with earlier claims (Takeuchi, 1997). Given that we found no distinction between expansion and contraction for the pure–target conditions [ $F(2, 32) < 1$ ], we have combined the data from both experiments. A subsequent linear trend analysis confirmed that the redundancy gain for pooled divergence flow was significant [ $F(1, 32) = 4.93, p = .017$ ].

Search for a specific direction of rotation revealed an altogether different pattern of data. For curl flow, increases in target redundancy provided no benefit in response time; there was a nonsignificant increase in response time of 4 ms as target number increased from one to four. Such a pattern implies little or no spatial parallelism, and any benefit in responding that might arise from the presentation of multiple rotating targets appears to be outweighed by the concomitant demands made on attentional resources. Taken together these data suggest that direction discrimination for homogeneous and divergence flows is a parallel, limited-capacity process, while the perception of curl direction appears to be serial-like in nature.

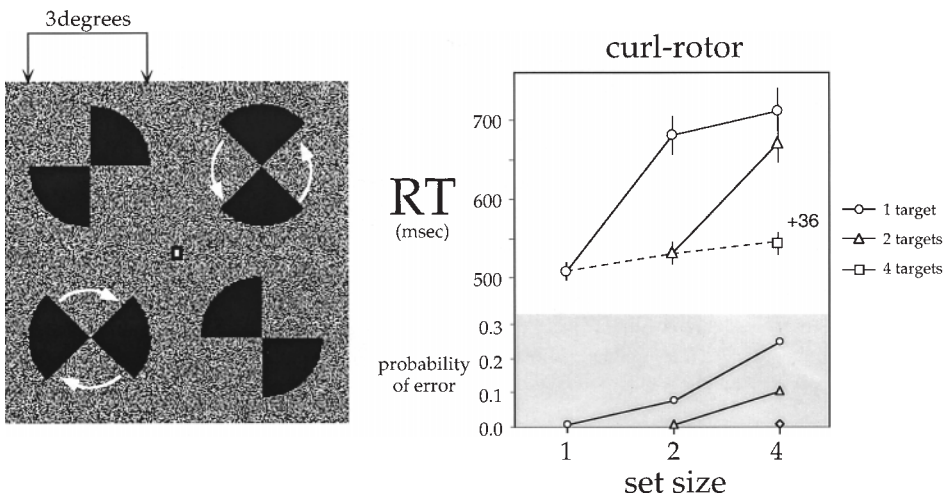
Figure 3 also shows associated error rates averaged over participants plotted for each condition and each flow type. Despite the fact that accuracy was loosely constrained in the collection of these reaction times, the pattern of error across conditions is virtually identical to those obtained for response time. Discriminations of the direction of homogeneous and divergence flow are made with increased fidelity as pure–target number increases, while curl

discrimination error rates are roughly flat across pure–target conditions.<sup>6</sup> The pattern of errors provides further assurance that the redundancy gains for the homogeneous and divergence conditions are not due to a speed/accuracy trade-off. Any adjustment of the RTs based on the observed trends in error rate would only serve to reinforce the observed effects.

*Introduction of occluding edges in rotation.* The previous search experiment was constructed to eliminate static cues as potential influences in search efficiency (e.g., changes in size or absolute position). Our goal was to equate the pictorial characteristics across animations so that perceptual differences could be uniquely attributed to motion. This was accomplished by using the same class of aperture-bounded textures across flow conditions. However, the various motion transformations that are applied to these textures to create curl, homogeneous, and divergence flow fields necessarily impose different relationships between the moving texture patch and the noise surround. For homogeneous and divergence motions there is accretion and deletion of object texture due to outflow and inflow within the circular aperture defined by the noise surround. In the case of curl flow, there is little if any accretion or deletion of background at the aperture border because the entire area circumscribed by the aperture is in rotation. Insofar as this dynamic cue may explain why only the curl data looks serial-like, it must be removed if we wish to interpret our results in terms of motion per se and not in terms of how particular motions happen to interact with the apertures. For this reason we have conducted an ancillary experiment that introduces accretion and deletion cues into a rotating stimulus. If this new rotary stimulus manifests signs of parallelism (i.e., pure–target redundancy gains), we will have implicated accretion and deletion as a possible source of the dissociation seen in Fig. 3.

The stimuli for this experiment are shown in Fig. 4 and consist of black hourglass shapes (rotors) that rotate over a static noise background. These types of rotary displays are a natural choice because they repeatedly occlude and reveal the static background texture as they spin, thus providing a strong set of accretion and deletion cues. The rotor stimuli were matched to our previous experiments in terms of duration, dimension, and interelement spacing. All aspects of the design of this experiment were identical to our previous search methods, with nine participants searching for clockwise rotation

<sup>6</sup> Given that the curl error rates are uniformly near zero for the pure–target conditions, there remains the possibility that the floor is obscuring decreases in error with target number. Such a decrease might implicate a trade-off of speed for accuracy as target number is increased. We have replicated the pattern of RT and error found in our initial *curl* condition with nine additional observers under an instruction set in which speed was further emphasized (pure–target error rates were slightly higher and flat, but still near floor). We also found remarkably similar results in a separate experiment in which nine observers searched for rotating stimuli with occluding edges (see ‘Introduction of Occluding Edges in Rotation’ under Results).



**FIG. 4.** Representative stimuli and results from the rotor-based *curl* experiment. The white arrows depict stimulus motion and were not included in the actual displays. The right panel plots means of medians as a function of set size and target number for nine subjects. Associated errors, averaged over subject, are plotted below for reference.

(the “target” direction) among a variable number of rotors that moved in either the target or distractor direction.

The results from the rotor experiment are plotted on the right in Fig. 4. In the case of rotor-based *curl* we again find evidence consistent with capacity limitation in that there are sharp increases in response time for single and double target conditions as the number of rotors moving in the distractor direction is increased (set size effect: 61 ms/item; indistinguishable from texture-based *curl*,  $t < 1$ ). In keeping with our previous findings for aperture-bounded *curl*, we see no evidence of redundancy gains in RT as the number of elements undergoing the target motion direction is increased. In fact, there is a substantial slowing of response time by 36 ms for the case in which four target motions were presented relative to the single-target baseline [ $F(1, 16) = 27.66$ ,  $p < .0001$ ]. Redundancy losses of this magnitude are difficult to explain in the context of idealized serial models which predict invariant RT across target number and provide additional evidence that acquisition of rotary sign in multielement displays is highly demanding of attention. Increases in RT with pure-target number are not entirely unusual in the use of the multiple-target search method; we have seen this particular data pattern for attentionally demanding discriminations of relative position (Thornton & Gilden, 2000).

As in our previous study, the pattern of RT is reinforced by an analysis of error making a speed/accuracy trade-off account of these data unlikely (see Fig. 4). That there is little evidence in this data set to support an efficient,

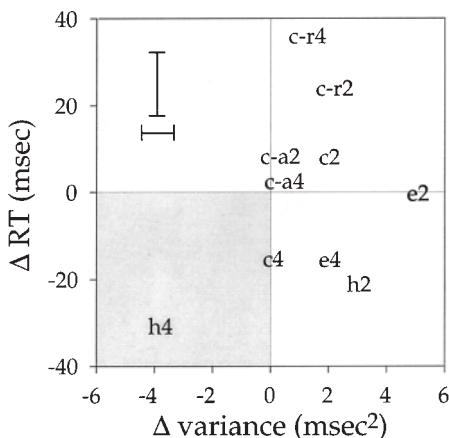
parallel process extends our earlier results with aperture-bounded rotation. More importantly, this experiment effectively rules out the possibility that the observed dissociation among flow types seen in multiple-target search is the product of stimulus-specific accretion/deletion relations.

*Favored positions analysis.* The power of multiple target search is in the inclusion of pure-target trials, wherein redundancy gains in RT can signal spatial parallelism in the presence of inefficient processing. Unfortunately, there is a confound associated with this method that must be addressed if we are to reliably link redundancy gains to parallel processing. It has been pointed out previously that associated decreases in RT with target redundancy can conceivably arise if observers have implicitly or explicitly adopted some "favored" spatial position across trials (Egeth & Mordkoff, 1991; Mullin, Egeth, & Mordkoff, 1988; van der Heijden et al., 1983). Such an explanation in no way invokes spatially parallel processing and holds that a favored positions effect, in conjunction with a serial process, can mimic redundancy gains. The idea here is that if, on any given trial there is a spatial position that receives privileged attentional processing, then on trials in which multiple targets are presented, there will be an increased likelihood that any one target element will fall within the favored location. There are several reasons to doubt such an explanation for the effects we report here. First, we have conducted individual observer analyses of response time as a function of location for trials in which only a single target was presented. In every case, results from these analyses reveal no reliable effect of position on RT, suggesting that in our experiments observers did not have a static, spatial bias. Second, and more importantly, any simple favored position argument would have to incorporate a motion contingency in that we do not find redundancy gains for all motion types.

While an analysis of single-target RTs by position may rule out fixed, favored positions models, it does not suffice to rule out the possibility that favored positions or attentional fixations are chosen randomly over trials (see van der Heijden et al., 1983). One possible method for evaluating a random, favored position model centers on a comparison of variability as pure-target number increases. If the observed redundancy gains are the result of random positional preferences, then variability should decrease as target number increases. When only a single target is present in the display, the random selection of spatial locations will necessarily lead to a mixture distribution defined by relatively fast response times (i.e., when a random attentional fixation is near the target element) and a higher percentage of relatively slow response times (i.e., when the fixation is farther from the target element). Although the exact mixture of fast and slow response times depends intimately on the distribution of attentional fixations, as target number increases the proportion of fast response times will grow relative to the proportion of slow response times by virtue of the increased likelihood that any given fixation or spatial preference will be near a target element. By this account, increasing the num-

ber of targets biases the mixture distribution toward fast response times at the expense of slow response times. This effectively decreases both the variability and mean of the overall response time for multiple target displays relative to single-target displays. Thus the prediction for a mechanism driven by random spatial biases is  $RT_4 < RT_2 < RT_1$  and  $\sigma_4^2 < \sigma_2^2 < \sigma_1^2$ , where the subscript represents pure-target number.

To test our data against this prediction we examined the degree to which the mean and variance for the observed pure-target conditions changed with set size for all motion types. In Fig. 5 we have plotted change in response time for the two- and four-target conditions ( $\Delta RT$ ) against the associated change in variance ( $\Delta \text{variance}$ ) for homogeneous, expanding, contracting, and curl flows (characteristic standard error bars are inset in the upper left for reference). Changes in response time and variance have been normalized across flow type by subtracting the respective one-target mean and variance from the means and variances of the one-, two-, and four-target conditions. In such a plot all one-target means and variances are brought into alignment at the origin. If the effects reported here are the result of random spatial biases, then all the data points in the plot should fall in the lower left quadrant. This gray region depicts the regime where both the mean and variance have decreased relative to the one-target baselines. As the figure makes clear, there is very little difference in variability across pure-target conditions, and the majority of reliable differences are clearly in the wrong direction. Such increases in variance as target number increases are inconsistent with a ran-



**FIG. 5.** A plot of normalized change in variability ( $\Delta \text{variance}$ ) against normalized change in response time ( $\Delta RT$ ) for the pure-target conditions [inset numbers (2 and 4) refer to target number, h is homogeneous, e is expansion, c is contraction, c-a is aperture bounded curl, c-r refers to the rotors]. The gray region in the lower left quadrant denotes the region where the data should fall if there are favored positions or random attentional fixations across trials.

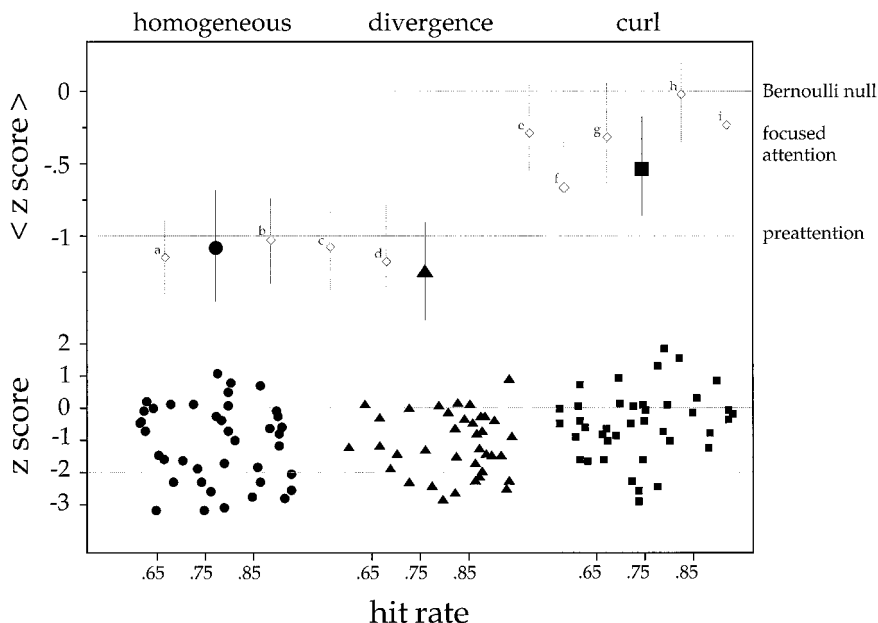
dom spatial bias account, providing further evidence that the redundancy gains we report are the product of spatial parallelism.<sup>7</sup>

### *Streak Formation in Signal Detection*

The analysis of outcome fluctuations in signal detection provides further support for the notion that direction analysis of curl fields is uniquely difficult and resource consuming. Figure 6 shows the ensemble average runs  $z$  scores for homogeneous, divergence, and curl flow fields along with their 95% confidence limits plotted in black. The lower portion of the figure shows the individual runs  $z$  scores for each participant in each condition. Recall that negative  $z$  scores in this context arise when sequences of discrimination outcome have fewer (and therefore longer) runs than would be expected if discrimination were actually a statistically stationary Bernoulli process. All three flow types show some streakiness in that they have distributions shifted below  $z = 0$ , the null specified by stationary outcome probability and trial independence. However, the distributions for homogeneous and divergence sequences are shifted a full standard deviation ( $M = -1.07$ ,  $M = -1.24$ ). The corresponding deviation from Bernoulli expectation is half as large in the case of curl ( $M = -.52$ ). Paired comparisons were conducted and no significant differences were found between the homogeneous and divergence ensembles. However, both homogeneous and divergence flows were significantly different from curl in terms of the magnitude of outcome clustering [ $t(4) = -3.405$ ,  $p < .05$ ;  $t(4) = -2.29$ ,  $p < .05$ ]. This statistical result is reiterated visually in Fig. 6: We see that the 95% confidence limits for both the homogeneous and divergence conditions do not overlap with the confidence limits obtained for curl. In addition, the homogeneous and divergence confidence limits overlap substantially with each other, and both include the point prediction for preattentive discrimination of  $-1$ .

These results are best appreciated when put in context with the ensemble of studies conducted by Gilden and Wilson (1995). Figure 6 shows how psychologically "simple" discriminations segregate from more demanding discriminations along the runs  $z$ -score continuum. Homogeneous and divergence flow are grouped with luminance, orientation, flash, and other preatten-

<sup>7</sup> We have also carried out extensive analyses of our data in the context of the *race-model* inequalities (Miller, 1982). Though this form of analysis is typically used to rule out separate activation accounts of redundancy gains in favor of coactivation models, it has also been suggested as a test of randomly varying favored positions in that serial models necessarily assume independent and separate processing of targets (see Mordkoff, Yantis, & Egeth, 1990). Analyses were carried out separately for each observer in the homogeneous, expansion, and contraction conditions. Results revealed small, but consistent effects of violation ranging from the 5th to 25th percentiles for those observers in which large redundancy gains were present. Though violation at any percentile provides evidence against both serial-based models and parallel, separate-activation models, it is important to realize that violations at these levels are driven primarily by a handful of relatively rare response times.



**FIG. 6.** Results of fluctuations in outcome (correct versus incorrect) during repeated discrimination. The top half of the figure shows ensemble averaged runs  $z$  scores (solid black symbols) and the associated 95% confidence limits for each of the three motion flow types. The lower portion of the figure shows the runs  $z$  score as a function of hit rate for each of the 120 individual sequences of 240 trials. The gray symbols included in the figure are taken from Gilden and Wilson (1995) and denote ensemble averages and 95% confidence limits for a variety of discriminations known to be either preattentive (a–d) or demanding of resources (e–i) [a = luminance; b = orientation; c = side missing; d = flash; e = 2 fractal; f = 1 fractal; g = tone 2IFC; h = ovateness; i = distance ratio]. See Gilden and Wilson (1995) for a complete exposition of these experiments.

tive dimensions of discrimination. Curl is isolated from the other flows and is associated with those discriminations requiring complex judgments of position (for example, fractal roughness, ovateness, and distance ratio).

## DISCUSSION

Multiple target search and analysis of the fluctuations in discrimination outcome provide consistent evidence that both homogeneous and divergence flow fields support parallel acquisition of sign with little capacity limitation. This evidence comes in the form of redundancy gains with multiple targets and outcome clustering in sign discrimination that is a full standard deviation from the expectation of trial independence. In contrast, the perception of sign in curl fields appears to be attentionally demanding; there was no benefit in search times with target redundancy, and rotation sign discrimination pro-

duced a level of outcome clustering that was on a par with other tasks requiring focused attention. These differences *cannot* be explained in terms of the inherent visibility of the various targets. We have explicitly shown that single-element curl and homogeneous stimuli were equally discriminable over eccentricity (see “Multiple-Target Search” under Methods), and all motions were placed at threshold in the streak studies (on average about 75% accuracy). The differences found are interpretable only in terms of how attention is allocated in the different motion domains.

Our work, while limited to relatively small numbers of motion elements, suggests that the visual system is implicitly tuned to distal motion and not to proximal flow. The attentional protocols wherein curl is segregated from homogeneous and divergence flow appear to be related to scene-based as opposed to image-based representations. In space, an object displacement can produce both homogeneous and divergence flow depending on the line of sight, and it is this equivalence that apparently underlies the common parallelism that was found. While these results are at variance with an earlier visual search study (Braddick & Holliday, 1991; but see Takeuchi, 1997), and are somewhat counterintuitive in terms of the physiology, we have found exactly the same distinctions in explicit memorial processes. Price and Gilden (2000) found that observers could only recognize rotation direction at chance in an “old/new” memory paradigm, while they were quite accurate in recognizing the directions of translating and expanding/contracting objects.

Despite the convergence that has emerged here, we are left with the problem of reconciling parallelism as it appears in visual search and parallelism as it appears in texture segmentation. One of the defining perceptual characteristics of a parallel process is the formation of boundaries that are aligned with regional differences in stimulus quality. It is the case that textures composed of translating structure segment on the basis of local sign, while textures composed of diverging flows do not. That homogeneous and divergence show similar levels of parallelism in multiple target search and streak formation implies that parallelism is not just one thing with unique perceptual consequences. While it is true that for most stimulus discriminations, texture segmentation and visual search converge to provide a common measure of attentional load, recent work has revealed a special class of discriminations for which these methods disagree. This class consists of conjunctively defined stimulus differences that support spatially parallel visual search, but presumably do not produce effortlessly segmenting regions (e.g., Rensink & Enns, 1995; Snowden, 1998; Wolfe, 1992).

There are a number of potential differences between search and texture segmentation tasks that may explain how this incongruity arises. One difference that seems especially relevant here concerns the extent to which each task makes use of spatial *integration*. The global region formation that occurs during visual processing of a texture requires massive spatial parallelism as



well as integration of the various outputs produced by such parallelism. In contrast, redundancy gains in a visual search task can arise from target evidence, that despite being acquired in parallel fashion, need not be integrated over space (see Raab, 1962, for such a model). There is a growing body of work that highlights the different roles that spatial pooling plays in search and texture segmentation tasks by cataloging the effects of irrelevant variation on performance (Callaghan, Lasaga, & Garner, 1986; Pashler, 1988; Snowden, 1998; Treisman, 1988; Wolfe, Chun, & Friedman-Hill, 1995). The general consensus that has emerged from this work is that texture segmentation tasks appear to require spatial pooling of local outputs, whereas visual search tasks do not. Spatial pooling leads, in the case of homogenous flow fields, to the grouping rule known as common fate as well as to a salient impression of depth ordering. The parallelism that is revealed in visual search for divergence does not involve pooling and merely reflects a simultaneous awareness of different directions.

It is the case that not all object motions have the same importance relative to the goals and activities of humans. It matters where objects are in the environment and the motions that take them from place to place are clearly something that any successful animal is going to have to pay attention to. Equally clear is that rotations confer little of interest to predation, avoidance behavior, or any activity that involves object positioning—for two reasons. First, the orientations of objects are themselves generally of little consequence. But more importantly, there is an underlying symmetry in rotation that is not present in translation; any orientation can be realized by either a clockwise or counterclockwise motion. The history of a rotation is thus lost in the final position, whereas the history of a general translation is not. The logic of attentional allocation revealed here, though unexpected in terms of motion physiology and complexity, is consistent with these basic boundary conditions imposed by our ecology (Proffitt, 1993). Though there has been little evidence to suggest an ecological division of motion types in the literature to date, the work reported here is based on converging support from two independent paradigms and provides the first substantive demonstration that the ecological significance of motion determines how attentional resources are used.

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