
Visual search for type of motion is based on simple motion primitives

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Abstract. Can we search for items based on their type of motion? We consider here visual search based on three types of motion: (i) ballistic motion, in which objects move in a straight line until they encounter a display boundary; (ii) random-walk motion, in which objects change direction randomly; (iii) composite motion, in which objects move with random fluctuations around a generally ballistic trajectory. The asymmetric pattern of search efficiency can be explained by assuming that visual attention is guided by processes sensitive to the presence of linear motion and change in motion. The results do not reveal a more sophisticated ability to segregate items based on the nature of their motion.

1 Introduction

Objects in the world move in different characteristic ways, and our visual system can use this information to help recognize objects (Newell et al 2004). Can we also use characteristic motion to find objects? We consider here visual search based on three types of motion: (i) ballistic motion, in which objects move in straight lines, changing direction only when they encounter a wall or similar obstacle; (ii) random-walk motion, in which objects change direction randomly; and (iii) composite motion, in which objects move along a generally ballistic trajectory with random fluctuations.

Ballistic motion may be characteristic of objects that have been pushed or thrown (ignoring the curvature imposed by gravity), while random-walk motion might be characteristic of objects that are not going anywhere in particular, for example, leaves fluttering in the wind. Composite motion may be characteristic of creatures moving under their own power; consider the typical path of a curious child.

Can we search for items on the basis of their type of motion? It has been suggested that the visual system has specialized mechanisms that guide attention to evolutionary relevant stimuli, such as snakes (Öhman et al 2001) (but see Lipp et al 2004) or angry faces (Hansen and Hansen 1988; but see Purcell et al 1996). There might be a similar adaptive advantage in being able to distinguish between the motion of an animal and a leaf in the wind.

We know that the difference between random-walk and ballistic motion is processed by the visual system, at least as a byproduct of motion deblurring processes (Watamaniuk 1992). Random-walk motion is also a discrete approximation of Brownian motion, and the visual system is sensitive to different forms of Brownian motion (Billock et al 2001). However, random-walk or Brownian motion has generally been used as noise, rather than as signal (eg Grzywacz et al 1995; Williams and Sekuler 1984). Here our object is to find out whether motion type can guide attention to likely targets. We present data from three visual-search experiments exploring the six possible pairings of these three types of motion. The pattern of results showed that search is sensitive to the presence of linear motion and to change in motion. The results do not reveal a more sophisticated ability to segregate items on the basis of the nature of their motion.

1.1 *Visual-search theory*

Visual searches for a target item among distractors vary in their efficiency. For efficient tasks, the number of distractors (set size) is relatively unimportant. The slope of the function relating reaction time (RT) to set size is near zero. If stimuli are briefly presented, these tasks remain easy and the function relating accuracy to set size is likewise flat. In inefficient search, RTs increase in a roughly linear manner with set size, typically yielding RT \times set size slopes of 20–40 ms per item when the target is present, even when all items are easy to classify and are large enough to be resolved without being fixated (Wolfe 1998). If items are hard to classify or difficult to resolve in the periphery, slopes can be arbitrarily steep. If stimuli are briefly presented, error rates rise with set size (Bergen and Julesz 1983).

Since the pioneering work of Treisman (1985; Treisman and Gelade 1980), much effort has gone into identifying the limited set of attributes that will support efficient search (reviewed in Wolfe and Horowitz 2004). Some attributes, like color and orientation, are firmly established. Others, like faces, continue to generate debate (Hershler and Hochstein 2005, 2006; VanRullen 2006).⁽¹⁾

Once an attribute has made the list, the hard work begins. While it is true that a search for red among green or vertical among horizontal will be efficient, not all color or orientation searches are so easy. Duncan and Humphreys (1989) summarized one set of constraints when they noted that search efficiency increases as the difference between target and distractors increases. Likewise, search efficiency decreases as the differences between distractors increases. The metrics defining ‘difference’ between two stimuli need to be worked out for each attribute. Feature spaces for visual search are not identical to the spaces defined by other psychophysical tasks such as rating scale or just noticeable difference (JND) methods. For example, in the case of color, the smallest difference between target and distractor that will support efficient search is much larger than a JND (Carter and Carter 1981; Nagy and Sanchez 1990). Moreover, the feature space for color search is not a scaled version of the space based on JNDs: whereas an equal-discriminability contour in color space describes an ellipse, minimum search times describe a quadrilateral; the signals from short and long wavelength cones appear to be combined differently in the two tasks (Nagy and Sanchez 1990).

Search asymmetries provide further evidence for the complex geometry of search feature spaces. In spaces defined by other psychophysical tasks (not to mention everyday physical space), the distance from A to B is the same as the distance from B to A. Not so in visual search, where search for A among B may be more efficient than search for B among A. Since Treisman’s early work on the topic (Treisman and Gormican 1988; Treisman and Souther 1985), search asymmetries have been considered important in defining the structure of feature spaces. Treisman has argued for two rules: first, that it is easier to find the presence of a feature than its absence. Hence, a moving target among stationary distractors is easy to find, but a stationary target among moving distractors is harder to find (Royden et al 2001). Treisman’s second rule is that the deviant stimulus ‘pops out’ from the standard. Thus, in this account, search for a tilted (eg 15°) line among vertical lines is easier than search for a vertical line among tilted lines because vertical is the standard and tilted the deviant. Wolfe (1994) proposed that many examples of the second rule are, in fact, versions of the first case. The search for tilted (left or right) among vertical can be described as a search for the presence of tilt, while search for vertical would be a search for the absence of tilt. Rosenholtz (2001) points out that many apparent asymmetries arise from asymmetries in experimental design. Search for one instance of a homogeneous set (eg a stationary item)

⁽¹⁾ A note about terminology: Where possible, we will try to use ‘feature’ to label specific instances of an ‘attribute’. Thus ‘red’ is a feature. Color is an attribute. A ‘feature space’ would be a description of all the features in an attribute. Thus, CIE color space would be a feature space.

among members of a heterogeneous set (eg items moving in all directions) is harder than vice versa. Still, there are asymmetries that cannot be attributed to the design. Why, for example, should it be harder to find an upright elephant silhouette among inverted than vice versa (Wolfe 2001), or to find Ns among mirror-reversed Ns than vice versa (Frith 1974; Malinowski and Hubner 2001; Wang et al 1994)?

1.2 *Searching for motion*

In this paper, we use search asymmetries to reveal some of the complexities of visual search for motion. Like color and orientation, motion is clearly an attribute that supports efficient search (Dick et al 1987; Nakayama and Silverman 1986), even in macaques (Buracas and Albright 1999). Motion can guide the deployment of attention in conjunction search tasks (McLeod et al 1988; von Mühlenen and Müller 1999, 2000).

However, not all aspects of motion work as guiding features. First-order motion supports efficient search, while second-order motion does not (Ashida et al 2001; Horowitz and Treisman 1994; Ivry and Cohen 1990). Different motion directions serve as features within the motion attribute. Thus, a target moving in one direction in the frontal plane will ‘pop out’ among distractors moving homogeneously in another direction (Thornton and Gilden 2001) (but see Driver et al 1992). On the other hand, rotation in the frontal plane does not appear to be a feature. Clockwise targets are hard to find amidst counter-clockwise distractors (Thornton and Gilden 2001; Watson and Humphreys 1999) (but see Ansorge et al 2006).

Motion in depth does not appear to be a strong feature. Stereo motion can be found but not very efficiently (Harris et al 1998). Expansion, an indication of motion in depth, can be found (Andersen and Kim 2001; Shirai and Yamaguchi 2004; Takeuchi 1997) among contracting distractors, while the reverse is more difficult. It is possible that search for expansion in these experiments is really a search for a change in size, rather than motion. However, since the same pattern is observed with random-dot patterns (von Mühlenen and Lleras 2003), this search asymmetry can be seen as evidence for an expansion motion feature.

Moving stimuli do give rise to search asymmetries. Dick (1989) found that search for a moving target among stationary distractors is reliably more efficient than search for a stationary target among moving distractors (under some circumstances, the reverse can also be true—see Pinto et al 2006). Rosenholtz (2001) pointed out that this could be considered an artifactual result. In Dick’s original experiment, moving stimuli could move in any direction. This means that search for stationary among moving was a search for a target among heterogeneous distractors while search for moving among stationary was a search for a target among homogeneous distractors. This is known to be easier (Duncan and Humphreys (1989). Royden et al (2001) performed a version where the moving distractors moved in only one direction. They found an asymmetry, though it was markedly less pronounced than the asymmetry seen when moving items could move in many directions. Curiously, when chimpanzees perform the same task, there is no difference between homogeneous and heterogeneous distractor motion (Matsuno and Tomonaga 2006).

The visual system can use speed to guide attention to a target of one speed among distractors of another speed (Driver et al 1992). A number of researchers have reported a search asymmetry for speed: search for fast among slow is efficient, while search for slow among fast is less efficient (Fencsik et al 2006; Ivry and Cohen 1992). However, these studies incorporated an asymmetric design (Rosenholtz 2001). Since stimuli move in multiple directions, targets and distractors were not symmetrically distributed in 2-D velocity space. Morvan and Wexler (2005) used a symmetric design in which stimuli moved in a single direction. They reported that, with brief presentations, search for fast targets among slow distractors produced higher accuracy than the reverse.

However, since they did not vary set size, we do not know whether there was an asymmetry in search efficiency.

Here, we report on a new set of search asymmetries between the three types of motion described at the start of the paper: ballistic, random walk, and composite. To anticipate the results, figure 1 shows the six pairs in order of search efficiency. Search efficiency varies widely across these conditions and each pair is strongly asymmetric. We propose that this pattern of results reflects the interaction between two aspects of motion processing, and illustrates the complexities of ‘preattentive’ processing of even the most basic of guiding attributes in visual search.

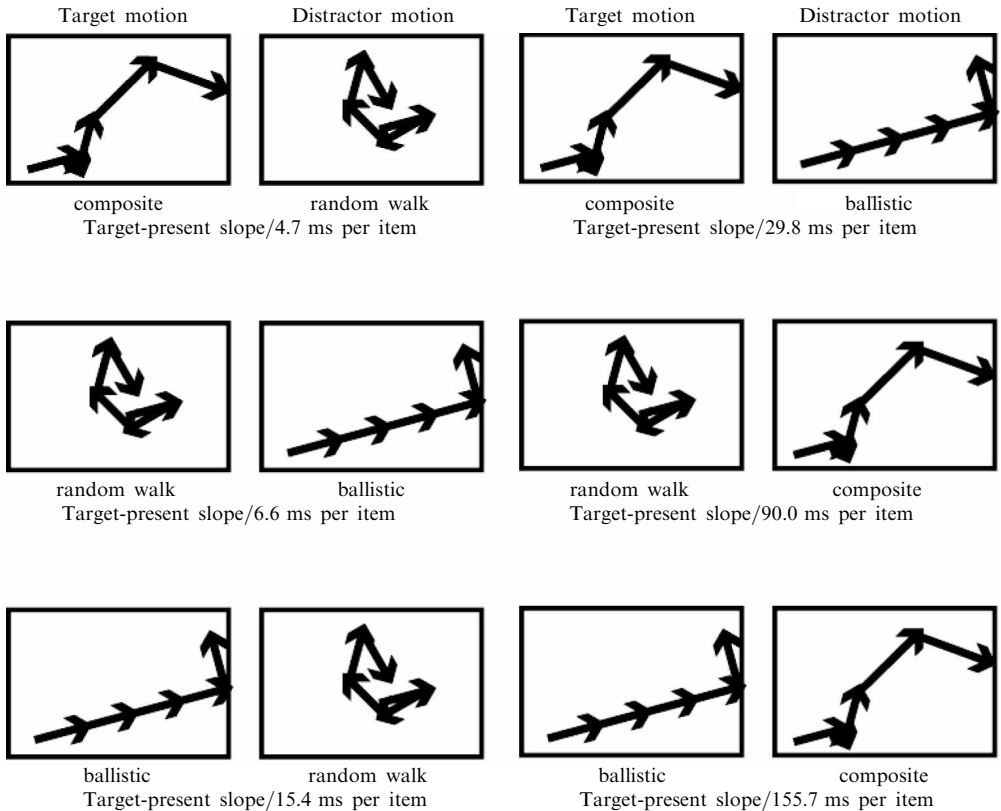


Figure 1. Target-present slopes for the six pair-wise combinations of three types of motion.

2 Methods

The experiment consisted of three sub-experiments, covering the three pair-wise comparisons of the three motion types. Each sub-experiment employed the search asymmetry design: observers were tested on search for a target defined by one type of motion against a background of distractors characterized by the other type, and then the target–distractor roles were reversed. The order in which each stimulus served as target or distractor was counterbalanced across observers.

2.1 Observers

Ten observers were recruited from the Brigham and Women’s Hospital Visual Attention Laboratory volunteer panel for each sub-experiment. Observers ranged in age from 18 to 55 years. All participants in our volunteer panel were screened for visual acuity (at least 20/25 when corrected) and color-blindness (with the Ishihara color screen).

Observers provided informed consent, following procedures approved by the Partner's Healthcare Corporation Institutional Review Board. Observers were compensated \$10 per hour for participation

2.2 Apparatus and stimuli

Stimuli were presented on a 21 inch color CRT (SuperScan Mc801 RasterOps and Mitsubishi Diamond Pro 91TXM); monitors were controlled by PowerMacintosh G4 computers (Mac OS 9.2.2) running Matlab 5.2.1 with Psychophysics Toolbox routines (Brainard 1997; Pelli 1997). Monitor spatial resolution was set to 1024×768 pixels, while displays subtended $36.1 \text{ deg} \times 27.1 \text{ deg}$ at a 57.4 cm viewing distance. Monitor refresh rates were set to 75 Hz (13.3 ms per frame).

Search stimuli were dark-gray disks with black borders, presented against a mid-gray background (see figure 2). The borders were present to help disambiguate cases where disks occluded one another (Viswanathan and Mingolla 2002). Disks subtended 1.5 deg , with the central dark-gray portion subtending 1.3 deg . The fixation cross subtended 0.9 deg .

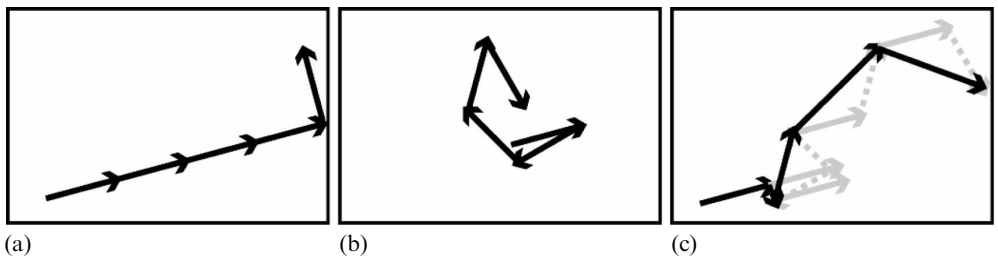


Figure 2. Motion types studied in these experiments. (a) Ballistic motion. An initial direction is selected (here 15°), and the direction does not change until the item reaches a display boundary, where it is reflected. (b) Random-walk motion, in which the direction changes on each frame of motion. (c) The random-walk vectors from (b) (broken-gray arrows) are added to the ballistic vectors from (a) (solid-gray arrows), to yield composite motion (black arrows).

At the start of each trial, stimulus positions were randomly selected from a 5×6 grid of possible starting locations, separated by 4.4 deg in the vertical and horizontal dimensions. Stimulus positions were updated every 27.7 ms, or two monitor refreshes. The frame-to-frame displacement for each disk was determined by combining two vectors, a ballistic vector and a random-walk vector. The direction of the ballistic vector was selected at random for each stimulus at the start of the trial, in increments of 15° . The direction of the ballistic vector remained constant until the stimulus reached a 3.2 deg buffer zone from the edge of the display, at which point the direction changed according to the laws of reflection. The direction of the random-walk vector was selected randomly (again in 15° increments) on each frame.

Different types of motion were defined by varying the magnitude of each vector. Pure ballistic motion was obtained by setting the magnitude of the ballistic vector to 8 deg s^{-1} and that of the random walk vector to 0. Pure random-walk motion was obtained by the reverse ratio. In composite motion, both vectors were set to 8 deg s^{-1} . These stimuli are illustrated in figure 2.

2.3 Procedure

Each trial began with the presentation of the fixation cross at the center of the screen. After 750 ms, 4, 7, or 10 moving disks appeared. On half of the trials, one of the disks was a target and the rest were distractors. On the remaining trials, only distractors were presented. Disks moved for 5 s, then the display was blanked. The observers' task was to report whether or not there was a target present, using the 'quote' key for 'yes' and the 'a' key for 'no'. Observers were asked to fixate at all times (the fixation cross

was present throughout the motion sequence), and to respond as quickly and accurately as possible. Observers were given printed feedback on the computer monitor indicating accuracy and RT on that trial. Additionally, the computer beeped on error trials. Feedback was presented for 1 s, after which the next trial began.

There were 300 trials, or 50 per cell. The first 3 trials were used to demonstrate the task to the observer, and were not included in the analyzed data.

2.4 Data analysis

We computed median RTs for all conditions, rather than discarding outliers. Medians were then used to derive the RT \times set-size slopes. Where appropriate, we report t -tests against 0 for slope values. Error rates were converted to the signal detection measure d' . Perfect performance was corrected by assuming half an error in any cell containing no errors (Macmillan and Creelman 2004).

3 Results

Figure 3 shows the average median RT and d' for each of the six pairings of motion types as a function of set size, with the accompanying least-squares regression lines. Note that all pairs are plotted on the same scale. The y -axis scale for target-absent RTs is twice that for target-present RTs. The y -axis for d' is inverted, to facilitate comparison with the RT data (poor performance is up).

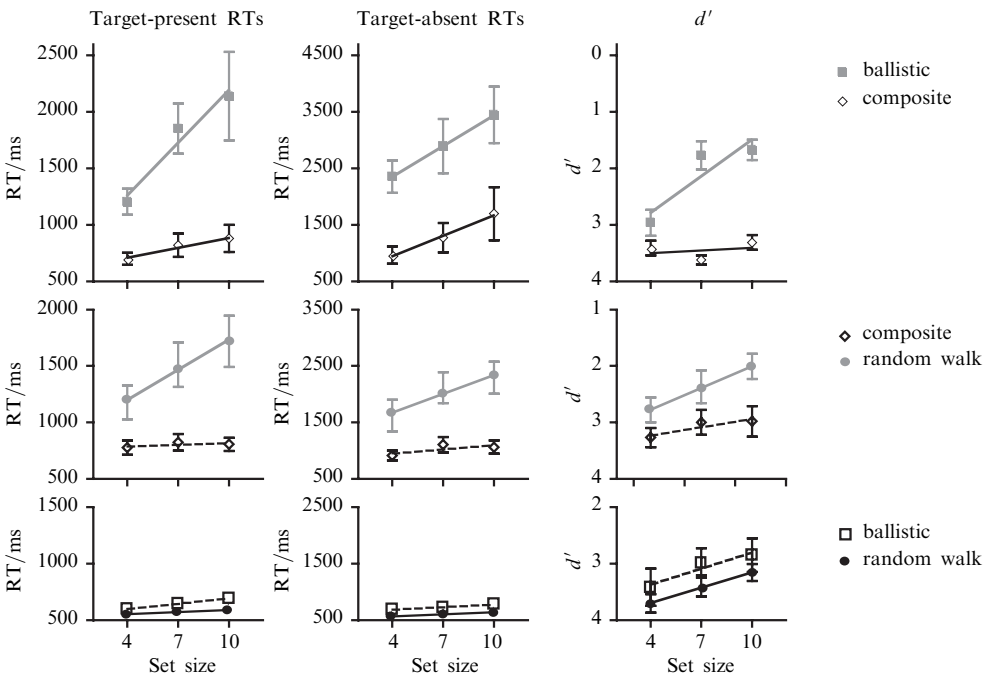


Figure 3. Average median RT and d' as a function of set size for all pairings of target and distractor motion. Each row presents data from a different sub-experiment. Note that all panels in a column are on the same vertical scale. Scale for target-absent RTs is twice that for target-present RTs. The y -axis for d' is inverted to facilitate comparison with RTs. Lines indicate the least-squares regression line. Error bars are ± 1 SEM.

All of the pairings produced search asymmetries in the RT domain. For target-present trials, slope asymmetries were reliable by paired t -tests (all $t_9 > 2.3$, $p < 0.05$). For the target-absent trials, while the trends were in the same direction in each case, the slope differences were not significant for the ballistic–random-walk and ballistic–composite pairings ($t_9 < 1.4$, $p > 0.2$). The composite–random-walk pairing did produce

a reliable target-absent slope asymmetry ($t_9 = 3.1, p < 0.05$). The pairings that did not show statistically reliable slope asymmetries still showed large asymmetries in median RT (ANOVA: ballistic–random-walk $F_{1,9} = 14.1, p < 0.004$; ballistic–composite $F_{1,9} = 28.4, p < 0.001$). We assume that target-present trials are terminated when the observer detects the target, while target-absent trials require more complex decision rules (Chun and Wolfe 1996; Cousineau and Shiffrin 2004). Thus, target-present trials are more informative for our current purposes, and we focus on these data in the remaining analyses.

Figure 4 shows the target-present slopes for all six conditions in rank order for comparison. Since each pair of conditions was tested with a different set of observers, we cannot evaluate the reliability of the rank ordering. As a substitute, we conducted t -tests on each adjacent pair of slopes. Only two tests were significant (both $ps < 0.05$): the slope for random-walk targets among composite distractors was significantly steeper than the slope for composite targets among ballistic distractors, and the slope for ballistic targets among random-walk distractors was steeper than the slope for the reverse search.⁽²⁾

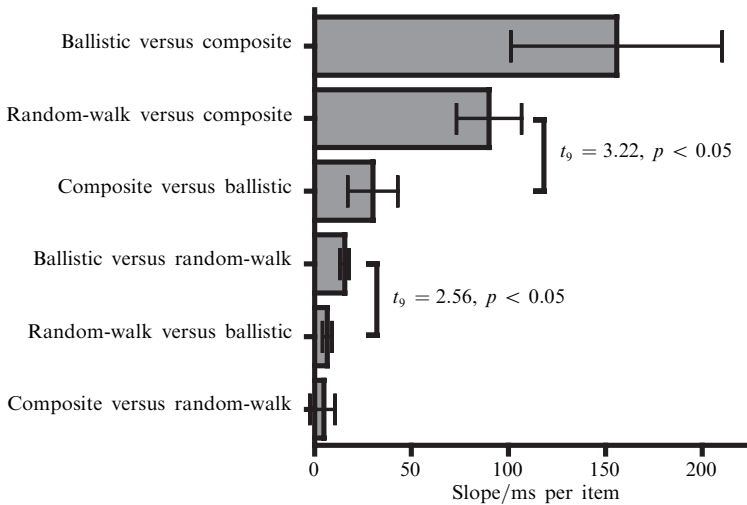


Figure 4. Mean slope for correct target-present trials for the six pairs of target versus distractor motions. Brackets denote pairs of slopes that differed significantly by t -test. Error bars are ± 1 SEM.

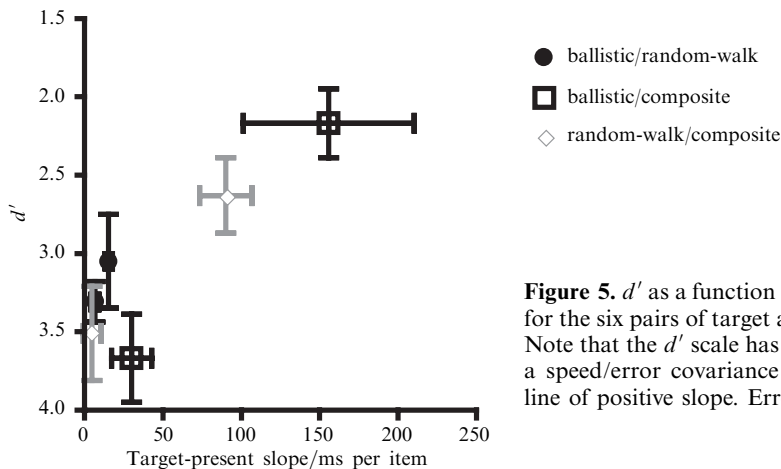


Figure 5. d' as a function of target-present slope for the six pairs of target and distractor motion. Note that the d' scale has been inverted, so that a speed/error covariance would show up as a line of positive slope. Error bars are ± 1 SEM.

⁽²⁾This test was paired. The other tests were unpaired.

The difference between conditions in this experiment could reflect nothing more than a particularly massive speed–accuracy tradeoff. A glance at figure 3 suggests that this is not the case. For each pairing, target-present RT, target-absent RT, and d' all show the same pattern. To illustrate this more clearly, we plotted d' against target-present slope for each pair of results (figure 5). It is clear from the figure that, in each pair, the condition producing less efficient search (ie greater slope) also produced lower d' values (plotted upward on the inverted scale in the figure). The data therefore do not reflect a speed–accuracy tradeoff.

4 Discussion

These results might appear somewhat mysterious. Consider, it is easy to find composite motion targets among random-walk motion distractors (4.7 ms per item). It is easy to find random-walk targets among ballistic motion distractors (6.6 ms per item). That would seem to suggest that search for composite-motion targets among ballistic motion distractors should be very efficient, but it is not (29.8 ms per item). This feels like a violation of some sort of transitivity principle (if $A < B$ and $B < C$, then $A \ll C$); however, it is not. A more productive way to think about this task is to hypothesize that two aspects of motion are guiding the deployment of attention: linear motion and change in motion direction. The results can be explained as the interaction of two asymmetries. First, it is easier to find more linear motion among less motion than to find less among more (see also von Mühlenen and Müller 2001). Second, it is easier to find more change among less than to find less change among more.

Integrated over more than a few frames, the linear motion velocity of random-walk stimuli will tend towards zero, while the velocity of ballistic motion and composite motion stimuli will be equal. Random-walk motion stimuli have a mean change in motion direction of 90° per frame. Adding the random-walk vector to the ballistic-motion vector yields a mean change of only 45° per frame for the composite motion stimuli. The ballistic motion stimuli have even lower mean motion change since they only change direction when they reach the display boundary.

In summary, we have the following three stimuli:

- Ballistic has high linear motion and low motion change.
- Random-walk has low linear motion but high motion change.
- Composite has high linear motion plus intermediate motion change.

Furthermore, there is no reason to believe that motion change and linear motion velocity are equally salient. In fact, in our data, the asymmetry between random-walk motion and ballistic motion leads us to believe that a 90° per frame motion change is more salient than 8 deg s^{-1} of linear motion.

With these assumptions in place, we can now look at the six tasks in increasing order of difficulty:

With composite motion among random-walk motion stimuli, both targets and distractors have motion change, but only the targets have linear motion. The result is an efficient search.

Random-walk motion among ballistic motion stimuli is efficient because it has a motion change feature that the ballistic motion distractors lack. The high linear motion of the distractors is not salient enough to impede search for the motion change target.

In search for ballistic motion among random-walk motion stimuli, the ballistic target has a linear motion feature that the distractors lack. However, the motion change of the distractors is highly salient, resulting in a somewhat less efficient, though still rapid, search.

Search for composite motion among ballistic motion stimuli is quite inefficient, even though the composite motion stimulus has a motion change signal that is missing from the ballistic motion stimulus. The addition of the linear motion component to

the random-walk motion weakens the motion change signal to the point where the presence of the change, while easier to find than the absence, does not ‘pop out’. If one systematically varied the size of the linear motion component of targets and distractors, search should become easier as linear motion becomes smaller.

Search for random-walk motion among composite motion stimuli is strikingly inefficient because the target is defined by the absence of the linear-motion signal. The addition of random motion change to both targets and distractors adds noise to the display, making the search harder than search for a moving target among stationary distractors.

Finally, ballistic motion among composite motion stimuli is an extremely inefficient and inaccurate search because it is the search for the absence of a relatively weak motion-change signal. Given that it was hard to search for the presence of that signal (composite motion among ballistic motion stimuli), it is predictable that it would be extremely hard to locate the absence of that signal.

The hypothesis broached at the outset was that these might be efficient searches because the mechanisms guiding search might be specialized to segregate motions of different types. These data seem better explained by invoking guidance toward linear motion and guidance toward motion change. That is sufficient to explain the searches that are efficient in this set of experiments: composite motion among random-walk motion stimuli, a search for linear motion; and random-walk motion among ballistic motion stimuli, a search for motion change. A more sophisticated ability to guide attention by motion type might have led to efficient search for ballistic motion among composite motion stimuli or random-walk motion among composite motion stimuli, but these tasks were inefficient and inaccurate.

5 Conclusions

The visual search feature space for motion seemed to be based on at least two attributes, linear motion and change in motion. These two attributes are sufficient to explain the data presented here. If we add motion direction (von Mühlenen and Müller 2001; Thornton and Gildea 2001), we can probably capture most of the literature on visual search for motion, though there are some complications. For example, is linear motion the same as speed or is it more like a spatial-length variable? Is change in motion direction a subset of a more general sensitivity to acceleration? To answer this, we would need to have observers search for items changing in direction among items that changed acceleration but continued in the same direction. Regardless of the answer to these questions, the present results indicate that the visual system does not seem to be able to guide attention by motion type, even though this information is used in other visual tasks. Instead, guidance relies on a coarse sampling of a simplified feature space. What you can see is not what you can search for.

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