Human heading judgments and object-based motion information

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Abstract

In four experiments, we explored observers’ ability to make heading judgments from simulated linear and circular translations through sparse forests and with pursuit fixation on one tree. We assessed observers’ performance and information use in both regression and factorial designs. In all experiments we found that observers used three sources of object-based information to make their judgments—the displacement direction of the nearest object seen (a heuristic), inward displacement towards the fovea (an invariant) and outward deceleration (a second invariant). We found no support for the idea that observers use motion information pooled over regions of the visual field. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Human beings and most other creatures must find their way through cluttered environments quickly and safely several times or more each day. Wayfinding is a term used in this context with the same meaning in the fields of perception and cognition, environmental psychology, geography and architecture (Lynch, 1960; Rieser, Doxsey, McCarrell & Brooks, 1982; Passini, 1984; Golledge & Stimson, 1987; Cornell, Heth & Broda, 1989; Peponis, Zimring & Choi, 1990; Scholnick, Fein & Campbell, 1990; Gärling & Evans, 1991; O’Neill, 1991; Devlin & Bernstein, 1995). For environmental psychologists, geographers and architects, to fail at wayfinding is to become lost. In human resource terms such loss can induce fear or distress, but at minimum it is a waste of time. To fail at wayfinding in traffic safety contexts can entail such losses, but amidst the plethora of technological means of conveyance around us, it is also to risk injury to oneself and others, and worse.

Wayfinding can be divided into several subtasks. Some, but not all, of these include: (a) an understanding of the general layout of the surrounding environment, or layout knowledge; (b) the ability to plot a path to attain some goal; (c) the ability to determine one’s success at following that path, typically discussed in the literature as the ability to make a heading judgment (where heading is the term used for the direction of movement); (d) the ability to detect potential contact with other obstacles, both stationary and moving, or collision avoidance; and (e) the ability to remember one’s passage sufficiently for a return trip. Our previous work has focused on three subtasks; layout knowledge (Cutting & Vishton, 1995; Cutting, 1996; Flückiger, Cutting & Baumberger, 1997), heading estimation (Cutting, 1986; Cutting, Springer, Braren & Johnson, 1992; Vishton & Cutting, 1995; Cutting, 1996; Cutting, Vishton, Flückiger, Baumberger & Gerndt, 1997) and collision detection (Baumberger, Chanderli & Flückiger, 1994; Cutting, Vishton & Braren, 1995). The focus of this article is on one aspect of layout perception (the relative depth of pairs of objects) and heading judgments. Our current views on heading can be characterized in seven tenets.
2. Seven tenets and a research principle about heading and its judgment

2.1. Tenet 1: human beings have mobile eyes in a mobile head; and as a consequence we, as pedestrians, rarely look in the direction we are going

Our emphasis is on pedestrians, for that is how we evolved, and our visual systems with us. At optical velocities faster than those attainable on foot, people often look in the direction they are going (Calvert, 1954; Appleyard, Lynch & Myer, 1964) or at things, such as the inner tangents of roadway curves, that are not physically stable objects at all (Raviv & Herman, 1991; Land & Lee, 1994). But as pedestrians, our eyes rove. One reason for this difference in eye-movement behavior is that, when in a car or train, the velocities of nearby objects off one’s path are too rapid to maintain gaze upon, a fact that apparently caused considerable eye strain for inexperienced travelers riding 19th century railroads (Schivelbusch, 1986).

The latter part of this tenet may be under appreciated. Perhaps the best data on naturalistic gaze patterns during gait come from Wagner, Baird & Barbaresi (1981). They took a Brunswikian, ecological survey of about 50 gazes from each of 16 pedestrians as they walked through a college campus and neighboring town. They found that such pedestrians spend only about 10% of the time looking within ±5° of their heading; indeed, the median angle between gaze and heading was about 20°. Moreover, they looked 60% of the time at stationary objects and 40% at moving objects (mostly people and cars). In both cases, they typically execute pursuit fixations (slow eye or head rotations, or both) to stabilize gaze on these objects.

2.2. Tenet 2: the typical flow pattern at the pedestrian’s eye is a conflation of the flow patterns due to translation and to eye (or head) rotation during pursuit fixation

Retinal flow is the proximal stimulus for heading perception, and for linear movement it is the sum of the radial flow pattern generated by translation and the unidirectional, lamellar pattern of rotation. The general characteristics of the retinal flow pattern were first noted by von Kries (1910) and formalized by Longuet-Higgins & Prazdny (1980) (see also Koenderink & van Doorn, 1987).

2.3. Tenet 3: pedestrians determine their instantaneous heading from the retinal flow pattern, without decomposition into translational and rotational components

In particular, the outward accelerations of transla-
tional flow are vectorially combined with the uniform velocities of rotational flow to yield signature information about heading direction. This statement is controversial, although not without its supporters (Perrone & Stone, 1994). Many algorithms exist for the explicit decomposition of retinal flow, and it is widely believed that some form of decomposition is performed by human travelers (Warren, 1995).

Our justification for this tenet comes from Cutting, Springer, Braren & Johnson (1992) (Experiment 8). In brief, a pedestrian’s pursuit fixations generate six flow patterns, three of translation (one forward along the heading vector, one vertical, and one horizontal, the latter two are oscillatory due to the bounce and sway of gait) and three of rotation (one from pursuit fixation, and the other two are rotational compensations of bounce and sway). With all six flow components, we found that observer performance was adequate to the heading task. But when the two oscillatory translations were removed, simplifying the conflation of flow patterns to four components, performance was considerably worse. Since it is difficult to imagine a decomposition scheme that works better with more components than with fewer, we concluded that explicit decomposition did not occur.

2.4. Tenet 4: pedestrians gain accurate nominal, even ordinal, but not necessarily absolute, information about their instantaneous heading from a given pursuit fixation

That is, displacement patterns in retinal flow specify whether a pedestrian is headed to the left or right of where he or she is looking, and comparisons across trials can indicate which pattern corresponds to a more eccentric heading, but these patterns do less well specifying how much one’s heading is left or right. This statement is also controversial; all other approaches to heading perception have assumed that visual flow yields absolute information about heading (Llewellyn, 1971; Johnston, White & Cumming, 1973; Warren, 1976; Warren, Morris & Kalish, 1988; Crowell & Banks, 1993; Perrone & Stone, 1994; Royden, Crowell & Banks, 1994; van den Berg & Brenner, 1994a,b). Here we primarily focus on nominal information.

Our justification for this tenet is given in Cutting, Vishton & Braren (1995) and Cutting, Vishton, Flückiger, Baumberger & Gerndt (1997) (Experiment 1). In brief, consider again cluttered environments with extensive layout information. We found that, as the simulated eye/head rotation of a pursuit fixation increased above 2°/s (due to either increased observer velocity or increased proximity of the fixation object), the accuracy of observers’ nominal heading judgments remained about the same, but their absolute accuracy deterio-
rated. Indeed, errors asymptoted to the magnitude of the gaze-heading angle. To be concrete, with a final gaze-heading angle of 12° (and a rotation rate of 5°/s), absolute errors burgeoned to more than 11°, but nominal errors remained almost unchanged. We believe that, interleaved with saccadic eye movements, the results of the sequence of successive pursuit fixations on either side of the heading vector help the pedestrian to hone in on his or her absolute heading.

2.5. Tenet 5: pedestrian’s use of motion information is supplemented by other visual and by extravisual information

Many studies suggest that auxiliary information about depth is used, including binocular disparities (van den Berg & Brenner, 1994b), occlusion (Cutting, Springer, Braren & Johnson, 1992) and height in the visual field (van den Berg & Brenner, 1994a). In addition, extravisual information may come from eye movements (Royden, Crowell & Banks, 1994; Banks, Ehrlich, Backus & Crowell, 1996), the vestibular apparatus (Marendaz, Stivalet, Barraclough & Walkowiak, 1993; Berthoz, Israël, Georges-François, Grasso & Tsuzuku, 1995) and from kinesthesia (Lee & Lishman, 1977; Flückiger, 1994). Our focus here, however, is on visual information from motion and depth and the visual consequences of eye movements.

2.6. Tenet 6: pedestrians use object-based motion patterns that are particular to particular objects in the surrounding layout

Cutting (1996) first described these patterns as ‘local’ sources of information, but we switch terminology here for two reasons: first, to emphasize that observers are paying attention to particular objects in the visual field, and second, to ally our discussion with the analyses, by Wallach (1965) and Cutting & Proffitt (1982) of object-relative motions. This tenet is controversial because most computational approaches to heading perception assume a combination, or pooling, of motions over relatively large regions of the visual field (Hildreth, 1992; Perrone & Stone, 1994; Warren & Saunders, 1995), but see also Kerzel & Hecht (1997). The experimental and theoretical focus on global, or pooled, motion information is understandable. Heading research owes its initiation to Gibson’s analyses (Gibson, 1950, 1979), which were certainly in this vein. And indeed, at relatively high speeds (measured in eye heights/s), such as landing an aircraft (a task with which Gibson began his studies of locomotion), the global flow pattern is quite apparent. For pedestrians traversing flat terrains, however, such patterns are not apparent. Thus, we have felt some other information might be used. In general, we suggest that pedestrians focus on and pay attention to particular objects, their relative motion and their ordinal depth (Tenet 5) at any given time.

2.7. Tenet 7: pedestrians use several types of object-based motions to guide their instantaneous heading judgments

At present, our list of motion sources contains three items: The displacement direction of the largest (or nearest) object (DDLO) in the field of view with respect to the more distant fixation object; inward motion (IM) of objects nearer than or farther than the fixated object; and outward deceleration (OD) of objects that are nearer than or farther than the fixation object. This tenet is also controversial, Cutting (1996) first proposed these three items, but Kim, Turvey & Growney (1996) suggested that the “experimental evidence for them is either limited... or circumstantial.” This particular collection of object-based sources is another focus of this article.

2.8. Research principle: observers in our heading-judgment experiments should perform at chance when none of the object-based sources of information is present

Perhaps it is not surprising from our seven tenets that our driving theoretical question is: Why do observers make any errors in heading judgments? Our view is that the key to understanding human heading judgments lies in understanding, not simply observers’ responses, but also the pattern of their errors; we believe that if one can predict the latter, one has a better theory. Given the specific information we have postulated and given their absence in a nominal heading judgment task, viewers should perform no better than chance. And they generally do not.

3. Object-based and field-based heading information

3.1. Object-based sources

The major purpose of this article is to explore further the bases of Tenet 7—the various object-based sources of information about heading. Cutting, Springer, Braren & Johnson (1992) first proposed that heading judgments were made on the basis of multiple sources of visual information. Indeed, their use was corroborated by extensive regression analyses on a large number of trials, with more than one source needed to account for errors and correct responses in the data. Moreover, when they examined those trials with none of these sources, observer performance was at, or even below, chance. The three sources used by Cutting,
Springer, Braren & Johnson (1992) were differential motion parallax (DMP, the motion direction of the fastest moving object in the field of view), IM and OD. Later, after reanalysis of the data of Cutting (1996) and Kim, Growney & Turvey (1996) suggested that DDLO should be substituted for DMP. DMP and DDLO were both highly correlated with the data, and with each other, but DDLO accounted for more variance. Like DMP, DDLO was not highly correlated with IM or OD.

This change in our source endorsement and the nature of these sources may provoke two additional queries. First, with Kim, Turvey & Growney (1996), one might wonder why a list of information sources would be labile, changing with new findings and new experiments. Our answer is two-fold. On the one hand, there are many ways to analyze the retinal and optical flow generated by movement through an environment, each of these yielding potentially different information. It is no mean methodological or statistical trick to discern which sources are used when so many are potentially intercorrelated. On the other hand, interviews with participants has been unproductive in revealing what they do; viewers appear to have no overt access to their wayfinding strategies. Thus, study of the current contenders has taken years of concerted effort, winnowing out possibilities.

Second, one might notice that the current list is somewhat odd in its makeup. It consists of one heuristic (DDLO) and two invariants (IM and OD)\(^1\). That is, DDLO is correlated with heading direction (the nearest object generally moves in the opposite direction from the heading vector) and, although that correlation increases the farther one gazes away from the heading vector, it is never perfect in the situations we have investigated. Thus, to use DDLO is to follow a good bet, not a sure one. To the contrary, if IM or OD are present and if one knows the layout (in particular, the ordinal depth) of the objects that generate them, and if for OD certain other conditions are met, they perfectly predict (\(r = 1.00\)) heading direction. A more detailed exposition of retinal flow is necessary to understand these three object-based sources.

3.1.1. The DDLO heuristic

When an observer moves along a linear path through the environment and looks directly in the direction of movement, the relative motions of the objects around him or her in the horizontal plane through the eye move as a function of three factors: the side of the path on which the objects lie (objects on the left move leftward; those on the right, rightward); the distance from the observer (objects twice the distance move with half the speed); and the angle of the object from the path (objects move as a function of the sine of the angle, zero along the heading vector and maximal at 90° from it). However, for purposes of this discussion, we only consider the direction, left or right, of flow for all objects in the field of view, as depicted in plan views.

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\(^1\)This amalgam theoretically mixes the metatheoretical approaches of indirect (cue-based) and direct (invariant-based) perception. Adopting a heuristic also violates directed perception (Cutting, 1986, 1991a,b), in that the heuristic does not specify what is to be perceived. We are working on bringing all of these ideas together, but that project is beyond the scope of this article.

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Fig. 1. Six plan views of the motion patterns of objects in an environment as they would project in retinal flow. Pedestrians are fixated on a particular object represented by a white, square dot. These are pertinent to discussions of the various sources of heading information. All panels show the observer moving linearly through the environment, portrayed as up the left-hand side of each panel. The left panels show analyses of flow to the left and to the right, relevant to the determination of the displacement direction of the largest (nearest) object in the field of view (DDLO); the right panels parse the flow differently, revealing the invariants of inward motion (IM) and outward deceleration (OD). The top two panels show this observer looking exactly in the direction of linear movement; the middle panels show gaze 20° to the right side; and the bottom panels show gaze 45° to the right. As one's gaze deviates from one's heading the regions of IM and OD in front of and behind the fixation object increase in size. In conjunction with the fixation object and knowledge about ordinal depth, Points a through d in the bottom-right panel, as explained in the text, can be used by the observer to predict heading direction with perfect accuracy.
in the left panels of Fig. 1. In the top left panel, at eye level, flow is nonexistent along the heading vector; it is leftward for all objects to the left; and it is rightward for all objects to the right. Binocular differences are ignored.

Now imagine a series of objects dropped randomly in front of the observer to either side of the path and within a cone of vision of 40° (the width of the computer screen used in these studies and in others). During the observer's movement, chances are 50% that the nearest object will move leftward, and 50% that it will move rightward. Thus, DDLO, would not provide any information about heading direction with respect to gaze; and indeed, it shouldn't since the situation in the panel is one where the observer is already looking in the direction of motion. But consider next two cases, shown in the middle- and bottom-left panels of Fig. 1, where the angle of gaze is displaced to the right of the heading vector. Such situations are by far the most common in everyday eye movement behavior (Calvert, 1954; Wagner, Baird & Barbaresi, 1981). In both cases the observer has continued to fixate on a particular object at a particular distance, executing a pursuit fixation. Notice that the rightward-motion field deforms around the fixated object, becoming smaller on fixation. Notice that the rightward-motion field deformations are by far the most common in everyday eye movement behavior (Calvert, 1954; Wagner, Baird & Barbaresi, 1981). In both cases the observer has continued to fixate on a particular object at a particular distance, executing a pursuit fixation. Notice that the rightward-motion field deforms around the fixated object, becoming smaller on fixation. Notice that the rightward-motion field deformations are by far the most common in everyday eye movement behavior (Calvert, 1954; Wagner, Baird & Barbaresi, 1981).

Consider two cases. If an object is placed at Point a in the lower-right panel of Fig. 1, if one knows that this object is farther than the fixation object, and if its IM is registered, heading direction is left of the fixation object. If, on the other hand, an object is placed at Point b, known to be closer than the fixation object, and its IM registered, once again heading direction is left of both objects. In this manner, IM, when combined with relative depth information (shown to facilitate heading judgments; Tenet 5), provides invariant information about heading direction.

3.1.3. OD as an invariant in retinal flow, and its constraints

Consider again the middle-right and lower-right panels of Fig. 1, and the two regions marked OD, one generally nearer than fixation and one generally farther away. If an object were placed at Point c in the third panel, its depth noted with respect to the fixation object and its OD registered, then heading is to the left of both; and if it were placed at Point d, known to be closer, and its OD registered, heading would also be to the left of both. In each case, heading direction is assured, but again its angular extent remains unknown.

Unlike IM, however, there are three constraints on OD. First, one must be looking within 45° of the heading vector (beyond 45°, the near and far regions seen in Fig. 1 begin to reverse sides). This constraint does not seem too taxing since Wagner, Baird & Barbaresi (1981) found that pedestrians look within 45° of their heading more than 90% of the time. Second, one must consider the displacements of objects only within a particular field of view, say 40° wide, or ±20° to either side of fixation. This is also probably not a serious constraint since static-resolution and motion-detection thresholds fall to about 10 and 30% of their foveal values at 20° eccentricity, respectively (Leibowitz, Johnson & Isabelle, 1972; Johnson & Leibowitz, 1979). Third, compared to velocities, accelerations and decelerations are difficult to detect. Two facts are rele-
Some contending field

Relations among object
noted that decelerations are detected easier than acceler-
ance in detection. On the other, Schmerler (1976)
Wang & Cutting, 1998), perhaps reflecting this differ-
ally more potent than outward deceleration (Cutting,
Albano & Harvitt, 1990) and Cutting (1996) called
motion registration system and depth system may be
the absolute heading can be determined. We call this
general method spatial pooling (Cutting, 1996), and a
related pooling scheme has been endorsed by Warren
& Saunders (1995). As with differential motion, a gen-
eral test of spatial pooling is provided below.

3.2.2. Spatial pooling

The second method is simpler: It adds the horizon-
tal components of all vectors for all nonfixation ob-
jects within a particular visual region. Again, the
difference vector of this sum generally points from the
center of the sampled region to the direction of the
heading; and again across many regions an estimate of
the absolute heading can be determined. We call this
general method spatial pooling (Cutting, 1996), and a
related pooling scheme has been endorsed by Warren
& Saunders (1995). As with differential motion, a gen-
eral test of spatial pooling is provided below.

3.2.3. Size-weighted spatial pooling

Neither differential motion nor simple spatial pooling
are concerned with the distance of the objects from the
observers; in fact, both are depth-independent calcula-
tions. This could be considered advantageous since the
visual system is often thought to be modular, and a
motion registration system and depth system may be
considered parts of separate modules. Nonetheless,
since depth information may play a role in heading
judgments (Tenet 5), a third method was suggested by
Cutting (1996) called size-weighted spatial pooling. In
it, the horizontal vector associated with each object in a
given region within the field of view is weighted by the
reciprocal of its distance (well-correlated with retinal
size for a field of objects of the about same physical
size), then all vectors within the region pooled. Again,
the difference vector of this sum will generally point in
the direction of the heading. The advantage of such a
method is that it mimics consideration of filled sectors
of the visual field, and thus more closely approximates
the plenum of what we see everyday.

3.1.4. Relations among object-based motion sources

OD and IM are orthogonal. That is, neither motion
exists at the same time for the same tree. The cate-
gories are exclusive. In addition, OD and DDLO are
orthogonal, at least for gazes within 45° of the headings
vector and again considering motion only within a
cone of about ±20°. Consider the middle panels of
Fig. 1 with a gaze 20° to the right of the heading. The
rightward motion (for DDLO) in the left panel does
not spatially overlap with either OD area in the right
panel except at eccentricities approaching 90°. In the
lower panels with a rightward gaze of 45°, this overlap
becomes slightly greater, but if one restricts the field
of view to about ±20° there is none. IM and DDLO,
on the other hand, have some small opportunity to
overlap. In the same lower panels, notice that the
region of rightward motion (which will contain DDLO)
does not spatially overlap with the more distant
region of IM (containing point a). However, the
nearer region of IM does overlap with the rightward
motion region. For small eccentricities of gaze from
the heading vector, this overlap is quite small. More-
over, empirically we determined that the cooccurrence
of IM and DDLO information carried by the same
tree occurred on less than 5% of all trials in the
experiments reported here. The reason is that greatest
initial gaze-heading angles were 8°.

3.2. Some contending field-based sources

As suggested earlier, our object-based view of infor-
mation used for heading judgments is nonstandard.
Most computational approaches focus on what we call
field-based sources of information, aggregating all mo-
tion across regions of the field of view. Pasternak,
Albano & Harvitt (1990) and Cutting (1996) called
these ‘global’ sources of information, but we have
changed terminology for two reasons: First, following
from the lead of Gibson (1950), these approaches fo-
cus on motion irrespective of objects that might be
fixed, and second because they are, ultimately,
thought to be based on the stimulation of the recep-
tive fields of certain cells, perhaps in cortical area MT
(Perrone & Stone, 1994). Three potential sources of
field-based information will be considered, each calcu-
lated by measuring and combining the motions of
objects in different ways.

3.2.1. Differential motion

The oldest computational pooling method stems
from Rieger & Lawton (1985) and Rieger & Toet
(1985). It has been endorsed and modified (Hildreth,
1992) or used as a benchmark (Heeger & Jepson, 1990,
1992), and has been called differential motion (Warren,
Morris & Kalish, 1988; Warren, 1995). In this ap-
proach, vectors are squared for each object in a given
region of the visual field to emphasize the motion of
objects nearby the observer (Rieger & Lawton, 1985).
All squared vectors are then summed, and a difference
vector determined (equal to the sum, but in the oppo-
site direction). For pedestrian movement across a plane
we need only consider the horizontal component of
each vector. For the retinal field around the fixation
object, this difference vector will generally point in the
direction of the location of the heading, and its magni-
itude will generally be proportional to the angular dis-
tance of the true heading from the center of the region.
Sampling many regions will give a set of difference
vectors that should converge on the heading. A partial
test of this method is provided in the next section.
Two questions arise. First, how successful are each of the object-based and field-based schemes at predicting the nominal direction of heading? Second, is there evidence that human beings use any of them? The second question is addressed in the experiments that follow, but the first also deserves an answer. In the next section we present computational data exploring the empirical efficacy of these six sources in a cluttered environment.

3.3. Computing the efficacy of object-based and field-based information for nominal heading judgments

3.3.1. Assumptions and methods

To test the object-based and field-based schemes, we considered a circular forest of trees, stretching into the distance around an observer who was instantaneously in its middle and walking linearly through it. The radius of the forest was 100 eye heights (roughly 160 m). Trees were planted stochastically, first starting with a rectangular grid, then perturbing them away from the intersections. On average the trees were placed five eye heights apart (along x- and z-axes), although the range was between two and eight eye heights. The top panel of Fig. 2 suggests how such an environment might appear to a pedestrian looking in the heading direction through a 40°-wide viewing aperture (such as a computer display).

We next assumed that the observer could look anywhere within ±90° of the heading, at any distance within the forest. Simulations were performed by moving a potential fixation tree to all possible locations within the circular forest. The forest was represented graphically with a radius of 400 pixels. The positions of the fixation tree were represented by every pixel in the plan view (xz plane) of the forward half of the forest (about 250000 locations). We assumed the observer would, for a brief time, execute a pursuit fixation following any such tree, with all other trees in the forest moving with respect to it. The relative motion vectors were then calculated for all other trees in the forest within a 40° cone of vision (±20° to either side of the temporary fixation tree). These were then compared, or combined in various ways, according to the nature of the computational model. After the calculation it was noted whether or not the model correctly predicted the direction of the heading vector from that location. These calculations were carried out in the spirit of an ideal-observer analysis (Geisler, 1984; Crowell & Banks, 1996), that is, no consideration was given as to whether the six variables could be picked up and used by observers, only that they conform to the predictions as each has been specified.

Shown in Fig. 3 are plan views of the patterns of success and failure of each source as a function of the position of the fixation object. Fuzzy dots represent the
locations of all the nonfixated trees, and the forests are identical in each panel. The location of the observer is along the left-hand, bottom edge of each panel (and in the center of the simulated forest). His or her path through the forest is linearly upward and near the left edge. The ragged edge of the circular forest can be seen in the upper right-hand corner of each panel. Most importantly the darker regions show the failures of each scheme (with the trees within that region not shown). Thus, were a fixation tree planted in any location within the darker region in each panel, the source of information would either not be present (IM and OD), or it would incorrectly predict the nominal direction of the heading (DDLO, differential motion, spatial pooling, and size-weighted spatial pooling). Most of the sources show neither a continuous nor smoothly curved area of failures. Such features are due to the placement of the trees, particularly in the foreground. Consider each panel in detail.

3.3.2. Nominal results for object-based sources

The object-based sources of information, shown in the three left-hand panels, fare quite well as predictors of nominal heading. In particular, DDLO fails only when the pedestrian is fixated on an object within two very small lobes within a few eye heights. The size of these lobes is determined by the proximity of the nearest tree on each side of the heading vector. Considering the entire area of the forward half of the forest, and considering a notion that the observer might look at all possible locations, DDLO would fail in 0.2% of all cases. If the observer spent all his or her time looking only within 5° of the heading vector, DDLO would fail in 0.01% of the cases. Clearly, DDLO reliably predicts nominal heading direction in a cluttered environment.

IM fares nearly as well, and failures occur only when the pedestrian is fixated on an object near his or her path, and then somewhat more so the farther the pedestrian looks into the distance. Again, considering the area of the forward semicircle of forest, and that an observer might look anywhere, IM would fail to occur in 0.6% of all cases. And again, were the observer constrained to look only within 5° of the heading vector, IM would fail to occur in 12.2% of the cases. Thus, IM is 100% reliable when it exists, and it occurs most of the time when traversing a cluttered environment, but not always available when looking near the heading vector.

OD is a bit more variable in its failures. It does not occur in regions both near the observer and near the heading vector in the distance. Considering all locations within the semicircular forest, OD would fail to occur in 2.3% of as cases, and constrained within 5° would fail to occur in 17.4% of the cases. Thus, OD is 100% reliable when it exists, and it too occurs most of the time when traversing a cluttered environment, but most often when looking somewhat off the heading vector.
3.3.3. Nominal results for field-based sources

The field-based sources as a whole did not fare as well. Differential motion, because it squares the vector lengths of more rapidly moving objects, almost always fails when the pedestrian is focused on an object within half the distance to the edge of the forest. This result is particularly damaging since Wagner, Baird & Barbaresi (1981) found that about 25% of all pursuit fixations were on objects less than about four eye heights away, and that one-half were on objects less than 14 eye heights away. Under nearby-fixation conditions, farther objects (which are more numerous) generate large vectors; these then dominate the computation, and the result is that the vector sum points in the direction of the heading, not away from it. Under the same assumptions made earlier, differential motion fails in 29.4% of all cases within the forward semicircular of the forest, and fails in 30.3% of the cases within 5° of the heading. Thus, differential motion is not a very reliable source of information for a moving observer.

Spatial pooling fares much better, and it is by far the best-performing field-based source of information. It fails to predict nominal heading only within two small lobes to either side of the heading vector near the pedestrian. In particular, it fails in only 2.4% of all cases within the forward semicircle of the forest, and in only 0.02% of the cases within 5° of the heading. Thus, spatial pooling would be very reliable, regardless of where one looks.3

Intermediate efficacy is demonstrated by size-weighted spatial pooling. It fails to either side of the heading vector when pedestrian is focused on near objects—in 9.8% of all cases within the forward semicircle of this forest, and in 10.0% of the cases within 5° of the heading. Thus, it would be moderately reliable and unconstrained by where one looks.

One might raise several objections to these simulations. Let us consider two sets, one concerning our procedures and assumptions and the other concerning computational theory.

3.3.4. Procedural objections and counterarguments

First, as noted above, the regions of success and failure vary somewhat with the placement of trees within the forest. Our retort is that, as long as one assumes that forest trees are planted stochastically but relatively evenly, the pattern variance is quite small. Second, one might object that, because occlusion of far trees by near ones will normally occur, the result is invalid. The effect of occlusion, however, is to limit the effective size of the forest, increasingly removing what can be seen in the distance. Moreover, in sample simulations with occlusions, we found these patterns, and the proportions of successes and failures, remained about the same. Third, one may object that, for the field-based sources of information, the cone within which we pooled all motions was too large (or perhaps too small). We used a value of ±20° around the fixation tree simply because this is the size of our display screen in our experiments. We also ran simulations with smaller (±19°) and larger (±60°) cones, and also weighted the vectors to be pooled within ±20° by the motion sensitivity function at various eccentricities. Results in each case were very similar to the patterns shown in Fig. 3, except that smaller windows create increased variance. Fourth, one might object that we have ignored ground texture. But to do so is equivalent to considering a more densely packed forest, and the patterns of results would be the same.

3.3.5. Theoretical objections and counterarguments

Three other objections, however, are much more important. First, one might object that the field-based pooling schemes discussed here—particularly differential motion and spatial pooling—were intended for use as methods subserving absolute heading judgments, not nominal judgments. Our response is two-fold. On the one hand, to compare models that measure a phenomenon with different measurement scales, one must reduce them to the scale with the least assumptions, in this case the nominal scale. This method is called scale convergence (Binbaum, 1983). No meaningful comparisons between models can be made otherwise. One can, however, estimate the minimal size of error for the field-based schemes from the right panels of Fig. 3. With differential motion, for example, there are many nominal failures 45° to the right of the heading stretching out from the observer to a distance of about 50 eye heights. All such failures mean an absolute error of at least 45° in a heading estimate. On the other hand, to attain absolute heading estimates, the field-based schemes arbitrarily divide the visual field into regions, compute the various vectors within those regions, and then compare the resulting vectors across regions. Such regions could simply be thought of as having been selected by sequences of saccades and fixations, and under a nominal model.

Second, in our implementation we have not allowed for variability and error in motion measurement. This is an important concern since field-based schemes are, in the absence of rotations, robust against error in the measurement of velocities. Our response is computational. That is, we reran the simulations above with the addition of random error. We selected an error value equal to the median absolute left or right component vector in the flow field without rotation due to pursuit fixation. We then created a noise range between plus (to

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3 This result goes against Warren & Saunders (1995), who concluded spatial pooling would work only for situations looking down the heading vector. Their approach, however, considered information for absolute heading; ours is for nominal heading.
3.3.6. Overview

Our computational analyses demonstrate that, across the forward visual field ±90° around the heading vector in a field filled with hundreds of trees, the object-based sources of information are more reliable than the field-based pooling schemes. Within ±5° of the heading vector, however, the pattern changes a bit: Spatial pooling is somewhat more reliable than OD and IM, and size-weighted spatial pooling is somewhat superior to OD. DDLO, however, is always superior to all three field-based calculations for this kind of environment.

Despite these differences, it is important to emphasize that many of the schemes do very well, particularly...
Linear Paths

Fig. 6. The data of Experiment 1 for linear paths, parsed by the presence of object-based sources of displacement information in stepwise regression. The top panels show the nominal-heading data ($N = 30$) and the bottom panels show the absolute-heading data ($N = 20$). The left panels show results parsed according to whether or not DDLO successfully predicted nominal heading in the stimuli; the middle panels show results parsed according to whether DDLO or IM or both were present versus when they were not; and the right panels show results parsed according to whether or not any of these object-based sources was present. After such regression, only the nominal data at 2 and 4° are statistically above chance.

4. Methodological overview of the four experiments

Experiments 1 and 2 explore heading judgments for observers on simulated straight (linear) paths, and Experiments 3 and 4 explore it for observers on simulated curved (circular) paths. Both are suggested in panels of Fig. 5. In all experiments, the sources of information investigated were those isolated by Cutting (1996)—the three object-based sources (DDLO, IM and OD) and the three field-based sources (differential motion, spatial pooling and size-weighted spatial pooling). On every trial in which these object-based sources were present, the information was carried by one or more of the six nonfixation trees, each planted stochastically within square cells on the ground plane around a seventh, central fixation tree. The cells are also suggested in Fig. 5.

Experiments 1 and 3 varied these information sources asystematically in a regression design. That is, each nonfixation tree was planted randomly within square cells of a grid, and the object-based sources of information measured post hoc for each of a large number of trials. These yielded vastly unequal numbers of trials with different combinations of the sources of information. Experiments 2 and 4 varied the object-based sources in factorial designs, systematically manipulating the placement of the trees across relatively few trials such that each source of object-based displacement information was represented equally often, and such that the occurrence of each was orthogonal in the stimulus set. In all experiments field-based sources were varied asystematically and measured post hoc on all the six moving trees in the visual display.

4.1. Stimuli

Motion sequences were generated on a Silicon Graphics Personal Iris Workstation (Model 4D/35GT, in Experiments 1 through 4), and on a Silicon Graphics Indy (Model R5000, in Experiment 1). Both displays have a resolution of 1280 × 1024 picture elements (pixels). Both have UNIX operating systems. Modal frame durations were 60 and 13 ms on the two machines respectively, but Vishton & Cutting (1995) (Experiment 5) showed that frame durations as long as 600 ms do not impede performance on these tasks. Interrupts were compensated for, paced by an internal clock, presenting stimuli where they should be in space after each interrupt occurred. This technique creates quite smooth motion, despite an occasional frame of twice the modal duration. Such interrupts generally occurred less than once per trial.

Sequences mimicked the movement of the pedestrian-observer through a small, sparse, wintry forest while fixating on a central tree. The simulated linear (Experiments 1 and 2) or tangential (Experiments 3 and 4) velocity of the observer was 2 m/s (a fast walk). Each tree was leafless, identical in physical shape, and (except in part of Experiment 1) identical in physical size as laid out in the environment. Each was rotated around the vertical axis to a new random orientation and placed at different locations on the ground plane. For canonical trees, the major branching of the tree limbs occurred at 1.1 eye heights (or 1.8 m for an individual...
with an eye height of 1.6 m), and the top of the highest branch was at 2.3 eye heights (3.7 m).

Each trial simulated the forward movement of the observer with gaze fixed on the central, red tree in the middle of the computer display. The six other trees (each a neutral gray) rotated and expanded around this fixation tree as simulated movement and gaze fixation progressed. The sky was cyan and the ground plane a light brown. The horizon was true for travel across a flat plane (that is, it was at 90° to the surface normal of the ground plane at the point occupied by the observer’s eye); it was not truncated in the distance by the clipping plane. As each trial began the fixation tree was at a distance of 14.7 eye heights (23.5 m for an observer with an eye height of 1.6 m). The angle between the line of gaze and the heading vector, called the gaze-heading angle, changed throughout the course of the trial. The values of the initial and final gaze-heading angles will be discussed in each experiment, and depended on whether linear or curved paths were simulated. Both are suggested in Fig. 5. For each trial in all experiments, motion continued for 4 s, and then the last frame remained on the screen until observers made their response. Such relatively long sequences were used because Vishton & Cutting (1995) showed that performance on this task only began to asymptote at trial durations of 4 s.

4.2. Procedure

Seventy-four members of the Cornell University community successfully completed the laboratory versions of the experiments. Each participated singly and viewed a different order of trials on the computer display directly in front of him or her at a distance of 0.5 m. The viewing screen subtended 40° of visual arc measured horizontally and 32° measured vertically, and perspective calculations for generating the stimuli corresponded to these values. Some observers were paid $10/hr for their participation, but most received course credit. An additional 122 observers participated in classroom versions of Experiments 2 and 4 for course credit. They viewed a single stimulus sequence en mass that was video recorded from the computer display. The video projection screen subtended 20° of visual angle as measured horizontally from the middle of the auditorium (range = 13–52°), and 16° vertically. Perspective calculations used to generate the sequences also corresponded to these values. All observers were naive to the purposes of the experiments at the time of their participation and were assumed to have normal or corrected-to-normal vision.

In all cases viewers were told they would be watching stimuli that simulated their own movement through an environment, and that the stimulus motion would also mimic their fixation on a central tree in the field of view. They were encouraged to keep their eyes at midscreen, but eye position was not monitored. Our rationale for this was fourfold. First, Cutting, Vishton, Flückiger, Baumberger & Gerndt (1997) (Experiment 1) monitored eye position on a fixation tree and found that performance was essentially the same as when viewers were told simply to keep their eyes there. Second, DDLO, IM and OD are present in the display and on the retina regardless of the observer’s gaze location. Moreover, gazing at an object anywhere on the screen creates an eye-movement feedback signal different than that experienced during real pedestrian gaze, and yet performance elsewhere (Cutting, Springer, Braren & Johnson, 1992; Vishton & Cutting, 1995) and here is adequate to the task. This suggests the necessity of such feedback under these situations. Third, no other heading study other than that of Warren & Hannon (1988, 1990), whose stimulus durations were comparable to ours, has monitored eye movements; and most have relied on observers fixated where told. And finally, we are currently investigating eye movements in a heading-judgment context (Cutting, Alliprandini, Creutz & Wang, 1998). Although those results are beyond the scope of this presentation, we have found nothing that compromises the interpretations here.

In the laboratory versions of all experiments, observers then manipulated a computer-controlled mouse to indicate their heading, and the next stimulus was begun after the response. In the classroom versions of Experiments 2 and 4, observers were given 4 s to write on an answer sheet their nominal response, R or L, indicating whether they were headed to the right or left of the fixation tree.

5. Experiment 1: heading direction from linear translation in a regression design

This study had three purposes. First, it replicated the stimulus configuration used by Cutting, Springer, Braren & Johnson (1992) (Experiment 1) and Kim, Growney & Turvey (1996). The former had very few trials relevant to the titration of information sources; the latter had many more, but the analyses of Cutting (1996) and of Kim, Growney & Turvey (1996) yielded discrepant conclusions. For purposes of replication, one group of participants watched each trial and gave a nominal response, pressing the left or right mouse key, indicating whether the trials simulated their movement to the left or right of the fixation tree.

Second, this experiment also examined two minor hypotheses, one concerning response mode and the other tree size. To this end, two additional groups were run. Both the second and third groups of subjects indicated their absolute heading at the end of each trial by manipulating the mouse-controlled cursor and plac-
ing it at the point on the horizon towards which they thought they were headed. These absolute values were analyzed in both a nominal manner indicating passage to left or right of the fixation tree, and an absolute manner indicating the exact position of the perceived heading in degrees of visual angle away from the fixation tree. In addition, the third group of observers saw two intermixed types of stimuli, one exactly like those of the first two groups and one in which the physical size of the trees was manipulated so that the largest appearing trees were never in front. Sample initial frames of both types are shown in the middle and lower panels of Fig. 2, respectively. This manipulation served to test whether DDLO was information generated by the largest object or the nearest object in the field of view. The latter possibility seemed most likely since Brunswik (1944) and Wagner, Baird & Barbaresi (1981) found that objects looked at during gait through the real world were roughly the same retinal size, regardless of distance.

Finally, given that we anticipated that these minor manipulations would create no systematic differences in the patterns of data, we planned to combine the results of the three groups, yielding a data base of a large number of trials and subjects for further analysis. Our purpose was that, because some of the results of Cutting et al. (1996) were above, but not statistically different from, chance performance, such effects might prove statistically reliable with a larger data set.

5.1. Method

Thirty-four individuals participated, but four were unable to perform the task above chance so their data were discarded. The remaining thirty (mean performance = 80%) were divided into three groups of ten. As suggested above, members of Group 1 responded nominally (left or right); those of Groups 2 and 3 gave absolute heading judgments. In addition members of Group 3 viewed trials in which retinal size was inversely correlated with distance (largest trees in the image were nearest), and in which it was positively correlated with distance (largest trees were farthest). This manipulation meant that the displacement direction of the largest objects were opposite in the two conditions on about 70% of all trials.

Each viewer responded to at least six practice trials. Those in Groups 2 and 3 had nominal feedback (a message presented on the screen indicating whether their placement of the cursor to the left or right of the fixation tree was correct); those in Group 1 had no feedback. Those with feedback were told that it concerned whether their response was in the appropriate direction with respect to the fixation tree, and that they should continue to place the cursor where they thought their true heading would be. All participants next viewed 96 experimental trials without feedback. For viewers in Groups 1 and 2 these trials were factorially divided into four initial gaze-heading angles (1, 2, 4 and 8°, with corresponding final gaze-heading values of 1.6, 3.1, 6.2 and 12.5°) × two sides of approach (to the left and right of the fixation tree) × 12 replications of each trial type with different sets of randomly positioned trees. For those in Group 3 the 96 trials consisted of factorial combinations of four gaze-heading angles × two sides × two size manipulations × six replications. Maximum simulated eye-rotation rate was 1.12°/s in the direction away from the heading vector, well within the limits suggested by Royden, Banks & Crowell (1992) and Royden (1994) for accurate heading judgments in pursuit–fixation displays, and among the modal rates computed from Wagner, Baird & Barbaresi (1981) and shown in Fig. 4. Including practice and debriefing, the experiment lasted about 20 min.

5.2. Results and discussion

5.2.1. Data combinations

Let us first outline the nonsignificant results that allow us to combine data. The data for Group 1 were taken as given, but the absolute data for Groups 2 and 3 were first scored nominally (whether or not the cursor was placed on the correct side of the fixation tree), and then groups compared. First, within Group 3, there was no significant difference between those trials with trees of the same physical size (retinal size inversely correlated with distance) and those with differing physical size (retinal size positively correlated with distance). Overall performance was 79 and 80%, respectively (F(1, 9) < 1). Thus, DDLO represents the displacement of the nearest, not largest, object in the field of view. This result again suggests that depth information is used in making heading judgments (Tenet 5). The data from the two sets of differently sized trees was then combined. Second, after this first combination, we found no significant differences among the three groups of viewers; overall performance was 78, 83 and 80% respectively, for Groups 1, 2 and 3 (F(2, 27) < 1). Next, across subjects in all groups here (and in the subsequent experiments) there was no difference in the side of approach to the fixation tree, with overall performance here of 79 and 81% for the left and right passage, respectively (F(1, 27) < 1). Finally, there were no differences in results for those observers whose trials were generated on the Iris versus the Indy. Thus, we can collapse across groups, and within subjects across sides of approach, yielding 30 viewers and 24 observations per viewer per gaze-heading angle.

Unsurprisingly, as in all of our previous research, there was a reliable effect of gaze-heading angle (F(3, 81) = 49.8, MSe = 11.13, P < 0.0001). Overall, viewers were 65, 77, 85 and 94% correct for initial
gaze-heading angles of 1, 2, 4 and 8°, respectively. Given a forward velocity of 2 m/s, Cutting, Springer, Braren & Johnson (1992) estimated that observers would need to know their heading within 3.75° to avoid collision with a stationary obstacle. Following Vishton & Cutting (1995) and Cutting, Vishton, Flückiger, Baumberger & Gerndt (1997), the gaze-heading angle data of each viewer were fit separately to logistics functions; 26 of 30 viewers met this criterion at a level of 75% performance, and 11 of 30 met it at a level of 95%. These proportions are somewhat lower than those found by Cutting, Vishton & Braren (1995), Vishton & Cutting (1995) and Cutting, Vishton, Flückiger, Baumberger & Gerndt (1997) whose displays had many more trees.

The viewers of Groups 2 and 3 also provided absolute data about their perceived headings. These groups were compared and no difference found between them ($F(1, 18) < 1$). Collapsing across approach sides (left and right), there was a reliable effect of gaze-heading angle ($F(3, 57) = 44.03$, $MSe = 1415$, $P < 0.0001$); mean cursor placements were at 0.64, 1.66, 2.76 and 4.65° to the correct side of the fixation tree, for initial gaze-heading angles of 1, 2, 4 and 8°, respectively. Remember, final gaze-heading angles were 1.6, 3.1, 6.2 and 12.5°, indicating mean errors in perceive absolute heading of about 1.0, 1.4, 3.4 and 7.9°, respectively. These results mirror those of Cutting, Vishton, Flückiger, Baumberger & Gerndt (1997) (Experiments 3 and 4), who drew the conclusion that, from such high nominal performance and such relatively poor absolute performance (errors as much as two-thirds the value of the perceived heading), one might characterize heading judgments from information in single pursuit fixations as nominal rather than absolute. Given the ordinal increase in responses, however, it is also clear that observers make comparisons across trials as well and can generally rank them according to eccentricity of gaze from heading.

5.2.2. Object-based sources and the nominal-heading data

More interesting for our purposes, however, are the results titrated with respect to DDLO, IM, and OD. For the nominal data, Table 1 gives the percent-correct performance and number of trials for each of the eight trial types at each of the four gaze-heading angles. With five possible variables predicting performance (subjects as a categorical variable, and gaze-heading angle and the presence or absence of the three sources of object-based information as continuous variables) there were reliable effects of DDLO, IM, and OD ($F(1, 2846) > 41.4$, $P < 0.0001$). Moreover, regression analyses on the individual subjects’ data showed 14/30 with a reliable effect of DDLO ($z = 0.05$), 7/30 with a reliable effect of IM, and 8/30 with a reliable effect of OD. Regressing these variables against the data at each gaze-heading angle, there were reliable effects of DDLO at all gaze-heading angles, reliable effects of IM at 2 and 4°, and a reliable effect of OD only at 2°. Finally, there were no reliable differences across viewers ($F(29, 2846) < 1$).

The three sources of information were generally uncorrelated across the set of 2880 trials, as shown in Table 2, $rs \leq 0.20$. These values compare reasonably well with those of Cutting, Springer, Braren & Johnson (1992) (Experiment 2, $rs < 0.15$) and Cutting (1996), $rs < 0.13$. In addition, DDLO correctly predicted true heading direction on 54, 59, 64 and 80% of all trials at initial gaze-heading angles of 1, 2, 4 and 8°, respectively; IM occurred on 9, 16, 28 and 55% of these trials; and OD occurred on 8, 16, 35 and 43%. These values are well below corresponding values in our simulations (Fig. 3) because of the sparseness of the environments used here. Finally, the likelihood that none of these information sources appeared on a given trial was 38, 29, 14 and 2%, respectively.

Since DDLO was the strongest predictor of the data, generally followed by IM and OD respectively, we will present our further analyses as a stepwise regression, as was done by Cutting, Springer, Braren & Johnson (1992) and Cutting (1996). These data are shown in the top panels of Fig. 6. The top-left panel shows the data.

<table>
<thead>
<tr>
<th>Trial type</th>
<th>Initial gaze-heading angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1°</td>
</tr>
<tr>
<td></td>
<td>%N</td>
</tr>
</tbody>
</table>

| Experiment 1 (30 viewers) | 100 (3) | 100 (11) | 97 (29) | 98 (105) |
| Experiment 2 (12 viewers) | 111 | — | 94 (96) | 94 (96) |

In the three digit code for the stimuli the first place stands for DDLO, or the displacement direction of the nearest, typically largest, object (1 = present, 0 = absent); the second place for IM, or inward displacement; and the third for OD, or outward deceleration. Thus, the Stimulus 011 has both IM and OD but not predictive DDLO.
Table 2
Intercorrelations of potential sources of information, and their correlations with the nominal and absolute data in Experiment 1

<table>
<thead>
<tr>
<th>Source intercorrelations</th>
<th>Field-based sources</th>
<th></th>
<th></th>
<th>Object-based sources</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Differential motion</td>
<td>Spatial Pooling</td>
<td>Size-weighted spatial pooling</td>
<td>DDLO</td>
<td>IM</td>
<td>OD</td>
</tr>
<tr>
<td>Spatial pooling</td>
<td>0.76</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Size-weighted spatial pooling</td>
<td>0.74</td>
<td>0.90</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>DDLO</td>
<td>0.29</td>
<td>0.46</td>
<td>0.52</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>IM</td>
<td>0.03</td>
<td>0.02</td>
<td>0.03</td>
<td>0.20</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>OD</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>—0.12</td>
<td>0.03</td>
<td>—</td>
</tr>
<tr>
<td>Correlations with the data</td>
<td>Nominal data ((N = 2880))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.04</td>
<td>0.08</td>
<td>0.09</td>
<td>0.26</td>
<td>0.19</td>
<td>0.09</td>
</tr>
<tr>
<td>After DDLO is partialled out</td>
<td>0.03</td>
<td>0.05</td>
<td>0.06</td>
<td>—</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Absolute data ((N = 1920))</td>
<td>0.09</td>
<td>0.13</td>
<td>0.15</td>
<td>0.28</td>
<td>0.21</td>
<td>0.10</td>
</tr>
<tr>
<td>After DDLO is partialled out</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>—</td>
<td>0.16</td>
<td>0.13</td>
</tr>
</tbody>
</table>

parsed first according to whether or not DDLO correctly predicted heading direction for each trial. Notice that performance was better in the presence of predictive DDLO with a mean of 17.5% better performance across gaze-heading angles. The top-middle panel shows the data parsed next according to whether IM or predictive DDLO, or both, occurred on a given trial versus those trials with neither. There was a mean of 18.5% difference between these functions. Finally, in the top-right panel, those trials with IM, OD, predictive DDLO, or any combination were present are pitted against those trials in which there were none of these sources of information. Here, there was a mean of 25.5% difference in the functions.

In addition, we performed a pair of regression analyses on the overall data that will prove useful as descriptive statistics here and in later experiments. That is, when the presence of predictive DDLO, of IM, and of OD were used as independent variables to predict the data across all trials, their linear combination accounted for 10% of the variance in the data \(F(3, 2876) = 103, \ P < 0.0001\). However, when the presence of any of the three sources (DDLO, IM or OD) was pitted against those stimuli without any information, this simple contrast accounted for 9% of the variance \(F(1, 2878) = 257, \ P < 0.0001\). Thus, the presence of any source accounts for the data about as well as linear combination of all three. Such a result suggests that observers may satisfice (Simon, 1955) when performing the heading judgment task; that is, they search for any adequate information in the stimulus sequence and respond on its basis.4

Two other trends in the data are worth considering. First, performance was relatively poor when none of these sources of information was present. Second, the function at gaze-heading angles 2 and 4° was nonetheless reliably above chance (Table 1). When performance was measured at these angles for each observer, then pooled across observers (rather than simply pooled across the data set) it was marginally above chance at 2° (with a mean performance level of 59%, \(t(29) = 2.04, \ P < 0.05\,\text{uncorrected for multiple comparisons}\), and substantially above chance at 4° (a mean of 77%, \(t(29) = 5.6, \ P < 0.001\)). In the analyses of Cutting, Springer, Braren & Johnson (1992) (Experiments 1 and 2) and Cutting (1996) none of the data at any gaze-heading angle remained above chance after removal of the object-based sources of information. Part of the rationale for this study was to provide a more powerful test of our research principle—that observers should perform at chance when no specified sources of information were present. Given that observer performance was above chance in the nominal data at 2 and 4°, it is clear that some residual information remains in these stimuli (Wang & Cutting, 1998).

5.2.3. Object-based sources and the absolute-heading data

The absolute data were regressed in the same fashion as the nominal data, using subjects, gaze-heading angle, and the presence or absence of the three object-based sources of information as predictors in a regression analysis. These data showed a reliable effect of DDLO \(F(1, 1896) = 81.7, \ P < 0.004\), but interestingly not of IM \(F(1, 1896) < 1\) or OD \(F(1, 1896) < 2.84, \ P > 0.08\), probably because of the increased variance in absolute results.

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4 Critics might suggest that this apparent intersubstitutability is simply due to a mischaracterization of the information available in our displays. That is always possible. However, any improved characterization must account for the differences shown in Figs. 5, 7, 10 and 12, where performance on trials with any of these three sources is vastly superior to those with none of the three. In years of search, we have yet to find method that parsed these results better than to postulate three difference sources of information (Wang & Cutting, 1998).
sponses. The bottom panels of Fig. 6 show the absolute placement of the cursor as a function of gaze-heading angle in stepwise regression format. The lower-left panel shows the placements on trials with and without DDLO, and a mean difference of 1.69° across all four gaze-heading angles. The lower-middle panel shows placements on trials with DDLO, IM or both, versus those without, and there was a mean difference of 1.56°. In the lower-right panel those trials with DDLO, IM, OD or any combination are compared with those without any of these sources of information, and there is a mean difference of 1.95°. Here, when none of these sources was present, the perceived location of heading was not significantly different than at the location of the fixation tree; observers had little idea of where they were headed. Finally, unlike the nominal data, there were striking individual differences in absolute heading responses ($F(19, 1896) = 11.0, P < 0.0001$), possibly suggesting different response strategies among the observers.

5.2.4. Inefficacy of field-based information

Effects and relations among differential motion, spatial pooling, and size-weighted spatial pooling were also assessed. Across all trials, these field-based sources were highly correlated with one another ($rs > 0.74$); they correlated reasonably highly with the presence of DDLO (median $r = 0.46$); and they were uncorrelated with IM and OD (median $r = 0.02$), all as shown in Table 2. When the six sources of information were all entered into an overall regression equation, the three field-based sources accounted for less than 1% of the variance in both the nominal ($F(1, 2872) < 1.37, P > 0.24$) and absolute data ($F(1, 1912) < 2.04, P > 0.15$). Fig. 7 shows the nominal and absolute performances for the 30 and 20 subjects respectively, for all trials parsed according to whether or not each of the three field-based sources were present. As one can see, some panels show some minor effects at small gaze-heading angles but none of the three field-based sources fares as well as DDLO (shown in Fig. 5), and all fall well below the predictive ability of DDLO, IM and OD combined.

5.3. Overview

Experiment 1 provided six results. First, corroborating Tenet 7, it replicated the findings of Cutting (1996) showing that three sources of object-based information (DDLO, IM and OD) accounted for a large proportion of the results when an observer is on a simulated linear path. Second, although performance was typically poor and at chance (for all the absolute data and for half the nominal data) when none of these sources was present, it nonetheless was above chance for the other half of the nominal data. Third, none of the field-based pooling schemes accounted for performance as well as DDLO, much less the linear combination of the three object-based sources. Fourth, varying the response measure (nominal versus absolute) had no effect on the nominal results. Fifth, absolute measures were considerably more variable across observers than nominal measures. And finally, the relative size of the trees had no effect on performance, proving that the pertinence of DDLO for heading perception is the proximity, not the retinal size, of foreground objects. In our displays proximity information is also carried by information in the height of each tree in the visual field.

6. Experiment 2: heading direction from linear translation in a factorial design

This second experiment had a single purpose: to manipulate the three object-based sources in an orthogonal manner and to observe the perceptual consequences. Previous studies of object-based
information—including Cutting, Springer, Braren & Johnson (1992), Cutting (1996) and Experiment 1 here—did not directly manipulate them. Instead, they measured the sources present in the stimuli after the fact. As shown in Table 1, this yielded loosely correlated sources of information occurring in vastly different numbers. Some may complain that regression designs fall prey to lopsided and asystematic presentation of information, thus reducing the interpretability of the results (Kim, Turvey & Growney, 1996). For purposes of generality, then, orthogonal stimuli were presented in two contexts—to observers singly in the laboratory and to observers en masse in a classroom.

6.1. Method

Eight types of stimulus trials were created, patterned after the analyses of Experiment 1 shown in Table 1. These presented the three sources of information (DDLO, IM and OD) in an orthogonal manner, yielding eight trial types. As in the top of Table 1, these were coded 111, 110, 101, 100, 011, 010, 001 and 000, with the first position in the code standing for presence (1) or absence (0) of predictive DDLO, the second for IM, and the third for OD.

In the laboratory setting of this study, fourteen new observers participated, but two did not perform above chance so their data were discarded. Like Group 1 in Experiment 1, the remaining twelve performed a nominal heading task (mean performance = 82%). Each observer was first given six practice trials with feedback, followed by 128 experimental trials without feedback: eight trial types × two tokens with different arrangements of trees × two initial gaze-heading angles (2 and 4°, with final angles of 3.1 and 6.2°, and with different arrangements of trees) × two approaches to the fixation tree (left and right, with the coordinates of each token mirror reflected around the heading axis) × two replications of each trial. Simulated eye-rotation rates were 0.28 and 0.56°/s. Including practice and debriefing, the experiment lasted about 20 min.

In the classroom setting of this experiment, 122 viewers participated for course credit. The data of all observers were included regardless of whether or not their overall performance was above chance. They first viewed three practice trials with feedback, and then a sequence of 32 trials without feedback. They wrote their nominal responses on an answer sheet during the 4 s intertrial interval. The test sequence consisted of eight different trial types × two tokens (at 4° initial gaze-heading angle only) × two approaches (left and right). The entire test took about 5 min. After the test, viewers indicated where they sat in the auditorium on a schematic map, and whether they were male or female.

6.2. Results and discussion

6.2.1. Object-based information in the laboratory setting

Despite the reduced range, there was a reliable effect of gaze-heading angle (F(1, 11) = 15.7, MSE = 0.18, P < 0.002), with overall performance of 84 and 90% at the 2 and 4° initial gaze-heading angles, respectively. More importantly for the focus of this paper, there were reliable effects of the presence or absence of the three sources of information: DDLO (F(1, 11) = 5.25, MSE = 0.34, P < 0.043), IM (F(1, 11) = 56.7, MSE = 0.61, P < 0.0001) and OD (F(1, 11) = 11.7, MSE = 0.18, P < 0.006). We then performed the regression analysis as in Experiment 1: Across subjects the three variables accounted for 15% of the variance in the data (F(3, 188) = 11.05, P < 0.001).

Perhaps more strikingly, however, there was a triple interaction of DDLO × IM × OD as suggested in the left panel of Fig. 8 (F(1, 11) = 30.3, MSE = 0.43, P < 0.0001). That is, performance on the seven types of stimuli with any source of information (DDLO, IM or OD) were not different from one another (F(6, 66) = 1.34, MSE = 1.33, P > 0.25), and together were vastly superior (mean of 91%) to those with no sources present (Stimuli 000 with 61%, t(11) = 1.78, P < 0.10). Across subjects this simple contrast accounted for 24% of the variance in the data (F(1, 190) = 61, P < 0.001), considerably more than the linear combination of the three stimulus effects in the factorial design. Such a result strongly suggests a satisficing strategy on the part of observers; they search for any adequate source of information and, when found, halt their search and respond.

6.2.2. Object-based information in the classroom setting

The classroom results mirrored those of the laboratory, as shown in the right panel of Fig. 8. There were reliable effects of DDLO, IM and OD (F(1, 121) > 20.2, MSE > 16.3, P < 0.0001). Observers’ performance across the seven stimulus types with at least one source of information was 86%, whereas performance on the stimuli with no sources was 46%. Regression analyses across subjects showed that the linear combination of the three factorial stimulus effects accounted for only 14% of the variance in the data (F(3, 971) = 54.1, P < 0.001), but the simple contrast between the seven stimulus types with information versus those without accounted for 20% of the variance in the data (F(1, 973) = 245, P < 0.001). Again, such a result suggests a satisficing strategy. Finally, performance on no-source stimuli (000) was below, but not reliably different than, chance (t(121) = −1.81, P > 0.07).

Interestingly, there was no effect of where observers sat within the auditorium, a result that replicates Cutting, Vishton, Flückiger, Baumberger & Gerndt (1997) (Experiment 4) for displays similar to these, as well
Linear Paths

Fig. 8. The data of Experiment 2 for linear paths. The left panel shows the data parsed according to the eight types of trials for the data gathered in the laboratory setting; the right panel shows this parsing for the data from the classroom setting. After all object-based information is removed, performance is at chance.

Gibson (1947) and of Goldstein (1987) for motion picture and static displays, respectively. This makes sense in our context since the relative motions in DDLO, IM and OD would not change as a function of the compressive slant of a screen seen from the side. There was also no effect of whether the viewer was male or female.

6.2.3. Inefficacy of field-based information

As in Experiment 1, regression analyses across stimuli revealed no reliable effects of differential motion, spatial pooling or size-weighted spatial pooling in either the laboratory setting ($F(1, 60) < 1$) or the classroom setting ($F(1, 28) = 1.42, P > 0.24$).

6.3. Overview

The results of this experiment corroborated and extended those of Experiment 1 and of Cutting (1996). That is, when orthogonally represented in the stimuli, three object-based sources of information more than adequately accounted for the perceivers’ data. More interestingly, performance seemed to be a function of whether at least one source of information was present; and the presence of more than one source did not affect the results. In addition, contrary to the nominal results of Experiment 1, there was no evidence for residual information in the stimuli when the three object-based sources were eliminated. This suggests that, whatever form the incompleteness of our theory, the residual data needed to be accounted for is relatively small. Finally, there was again no evidence that, in determining their nominal heading, observers pool the motions of objects in the visual field.

7. Experiment 3: heading and path direction from circular translation in a regression design

Pedestrians do not walk with linear precision during their travels. Even when moving generally straight, forward motion is accompanied by a bounce and sway induced by bipedal footfall. These cause no additional difficulties for heading judgments (Cutting, Springer, Braren & Johnson, 1992; Vishton & Cutting, 1995; Kim, Growney & Turvey, 1996). Pedestrians also weave and turn during the course of gait, generating curved paths and the optical and retinal flow patterns that accompany them. In Tenet 1, we noted that pedestrians rarely looked in their heading direction, which occupies a point in the visual field for linear translation. That tenet is especially true for curved paths, in part because the heading direction is no longer a point; instantaneous heading constantly changes. This is yet another reason why we prefer to think of heading judgments as nominal. On a curved path one cannot point exactly in the direction one is going, but one might always be able to say whether it is curving right or left.
For our purposes, curved paths are also interesting because, strictly speaking, the interpretation of the results of Experiments 1 and 2, as well as those of Cutting, Springer, Braren & Johnson (1992) and Cutting (1996), is confined to heading judgments from linear paths. Moreover, although Cutting (1986) (Experiments 10 and 11), Warren, Mestre, Blackwell & Morris (1991), Sauvan & Bonnet (1993), Stone & Perrone (1997) and Kerzel & Hecht (1997) have assessed observer’s heading performance on simulated circular paths, heretofore we have performed no error analysis for observers on circular paths, parsed by the presence or absence of object-based sources of information. Indeed, this was a concern of Kim, Turvey & Growney (1996), who suggested that “the idiosyncrasies... (of) IM, OD and OA) occur only when an observer translates rectilinearly...” This statement, however, is incorrect. As shown in Fig. 9 the patterns of IM, OD and OA occur roughly in the same manner for pedestrians on circular paths as on linear paths (see in the right-hand panels of Fig. 1).

One’s instantaneous heading is always linearly ahead, but a path along a curve will continuously change. Thus, there are two possible judgments one could make. One may be able to respond to whether one’s instantaneous heading at the end of the stimulus sequence lies to the left or right of the fixation tree—which we will call a heading judgment; or to whether one’s path, when continued into the future, lies to the left or right of the fixation tree—which we will call a path judgment. These possibilities are suggested in plan views in right-hand panels of Fig. 5. Notice that in this setting one can dissociate heading and path judgments. That is, as seen in the rightmost panel, at the end of the simulated circular path, the instantaneous heading lies to the right of the central fixation tree (indicated by the tangent to the circular path at the end of the sequence) but the future transit of the circular path lies to the left of the tree (indicated by the dotted line).

We had particular interest in path versus heading judgments. Warren, Mestre, Blackwell & Morris (1991) asked their subjects to perform a path-judgment task and accrued data in its support. On the basis of the results of Cutting, Vishton, Flückiger, Baumberger & Gerndt (1997) (Experiments 3 and 4) we had some doubts about the generality of this result when instantaneous simulated gaze did not change with a curving path. In our studies, although nominal heading performance remained adequate, observers seemed to have difficulty determining whether they were on a straight or a curved path, and there were considerable individual differences.

7.1. Method

Each trial simulated observer movement along a circular path. These paths had one of three radii; 50, 100 and 200 eye heights (or 80, 160 and 320 m), the same as used by Warren, Mestre, Blackwell & Morris (1991). While on that path, fixation was simulated on the central, red tree displaced from the path so that final angles between simulated gaze and the curved path abreast of the fixation tree, which we will call the path transit angles, were 1, 2, 4 and 8°. Half of the transit angles were to the inside and half to the outside of the circular path. Final gaze-heading angles varied with both path transit angle and radius, and values fell between −4.7 and 13°. Negative angles are those to the opposite side of the fixation tree. Simulated eye rotations were opposite the direction of path curvature for positive values, and in the direction of the curvature for negative values. Maximum simulated rotations were 1.25°/s.

Twenty-six observers participated but the performance of four was not above chance so their data were discarded. The remaining 22 (mean path-judgment performance = 66%) participated in two groups. The responses of Group 1 were nominal and those of Group 2 absolute. Members of Group 1 (N = 12) viewed random sequences of 96 trials: four final gaze-path transit angles (1, 2, 4 and 8°) × three path radii × two sides of the path (gazing into the circle and gazing outside the circle) × two paths of approach (left and right of the fixation tree) × two replications of each trial type with differently positioned nonfixation trees. They were asked to respond with a path judgment, using the mouse keys, indicating whether their path would pass to the left or to the right of the fixation tree. They were given a practice sequence of six trials with feedback about where their path transit (or future path) was to the left or right.

Members of Group 2 (N = 10) viewed two different sequences of 96 trials, each like those for Group 1.
However, for one set they were specifically instructed to respond judging their path transit (future path), placing the cursor to left or right of the fixation tree and at its distance, and for the other set they were specifically instructed to respond judging their instantaneous heading at the end of the sequence (left or right) of the fixation tree and at its distance. Observers were shown representations of curved paths and of the instantaneous heading superimposed during, or at the end of, six practice trial sequences. Interrogation confirmed that observers felt they understood the difference; each was confident of his or her ability to do each task. Half of the observers participated first in the heading-judgment task and then the path-judgment task; the other half participated in reverse order.

7.2. Results and discussion

7.2.1. Future path or instantaneous heading?

The data of Group 1 were analyzed first and are shown in the top-left panel of Fig. 10. They were parsed, according to gaze-path angle and path curvature and, by whether the stimuli simulated looking into the circular path or out from it. Overall performance was 70%. There were three reliable main effects: gaze-path transit angle \((F(3, 33) = 23.1, \text{MSE} = 5.3, \ P < 0.0001)\), path radius \((F(2, 22) = 10.8, \text{MSE} = 2.72, \ P < 0.001)\), and direction of gaze with respect to the circle, in or out \((F(1, 11) = 40.2, \text{MSE} = 42.7, \ P < 0.0001)\). Regression analysis showed that these three variables accounted for 9% of the variance in the data. There was also a third-order interaction involving these variables \((F(6, 66) = 2.44, \text{MSE} = 0.22, \ P < 0.04)\), and aspects of this interaction prove of particular interest.

Rather than accepting these patterns of results as given, we felt that there may be some other cause for them. Remember, the experimental design was factorial in terms of the path-transit angle, not the final instantaneous heading angle. We first noticed that if path transit and final heading angle were on the same side of the fixation tree (middle panel of Fig. 5) overall performance was 85%, but that if they were on different sides (right panel of Fig. 5) performance was 27%. Thus, we decided to reanalyze the data as a regression analysis according to the instantaneous gaze-heading angle at the end of each trial. These data are shown in the top-right panel of Fig. 10.

Analyzed in this manner, overall performance burgeoned to 82%, up 12% from the previous analysis. Moreover, the instantaneous heading angle now accounted for 26% of the variance in the data \((F(1, 1139) = 384, \ P < 0.0001)\); and when other three variables of factorial design were also entered into the regression equation they accounted for only 2% more variance. The data were also fairly stable across observers; there were no statistically reliable individual differ-
ences ($F(11,1139) = 1.56$, $P > 0.10$). Thus, it is clear that these viewers, despite our instructions, were judging their instantaneous heading angle, not their future path.

Because our Group 1 data contrasted with claims in the literature, we felt they were in need of replication. Therefore, consider next the data of Group 2. The middle panels of Fig. 10 show the data of this group under the heading-judgment instructions and the bottom panels show them under the path-judgment instructions; the left panels show the data plotted by path-transit angle, and the right panels by the instantaneous heading angle. It should be clear that instructions mattered not at all ($F(1,9) < 1$); in both cases Group 2 observers performed roughly as did the Group 1 observers—they judged instantaneous heading angle rather than path transit.

In particular, with respect to the factorial design, there were reliable effects of path-transit angle ($F(3,27), \text{MSe} = 0.25$, $P < 0.001$), and direction of gaze with respect to the circular path ($F(1,9) = 40$, $\text{MSe} = 29.9$, $P < 0.0001$), but none for path radius ($F(1,9) < 1$). A regression analysis showed that, together, these three variables accounted for 2% of the variance in the data. There were also reliable interactions of path-transit angle $\times$ gaze in or gaze out ($F(3,27) = 3.2$, $\text{MSe} = 0.37$, $P < 0.04$), and of path radius $\times$ gaze in or gaze out ($F(2,18) = 15.82$, $\text{MSe} = 0.29$, $P < 0.0001$). As with the data of Group 1, there was a striking discrepancy in performance between judgments when final heading and path lay on the same side of the fixation tree (76%), than when they lay on opposite sides (41%). As with the Group 1 data, regression analysis showed that final gaze-heading angle accounted for 10% of the variance, with no residual contributions of path-transit angle, gaze into or out from the circular path, or path radius. Indeed, when performance was analyzed by heading judgments observers were 71 and 72% correct in the two conditions, respectively. When the data were analyzed by path transit, they were 60 and 61% correct.

One can see, however, that the Group 2 data are not quite as striking as those for Group 1. This seems likely due to the task-order $\times$ path-transit angle $\times$ radius $\times$ side interaction ($F(6,54) = 8.8$, $P < 0.001$); that is, regardless of instructions, Group 2 observers performed more like Group 1 observers on their first task than on their second. This seems likely due to some confusion about how the second task might differ from the first. Regardless, under both sets of instructions our observers more clearly judged their instantaneous heading, not their future path.

### 7.2.2. Efficacy of object-based information, but mostly IM

Regression analyses were then performed on the data using the final gaze-heading angles and the three object-based sources of information, as in Experiment 1. Across the 22 observers, these showed reliable effects of gaze-heading angle, DDLO and IM ($F(1,3044) = 35.6$, $11.1$ and 29.1, $P < 0.001$) and a weaker effect of OD ($F(1,3044) = 4.5$, $P < 0.03$). For display purposes the final gaze-heading angles were then sorted into four bins; less than 1.5°, between 1.5 and 3.0°, between 3.0 and 6.0° and greater than 6.0°. The results are shown in Fig. 11 and Table 3 for the eight trial types. Since IM was the most potent of the three sources in this analysis, those trials with IM are compared to those without in the upper left-hand panel, with a mean performance difference of 17% across the bins of gaze-heading angles. The upper-middle panel combines those trials with IM with those having predictive DDLO yielding a mean difference of 14%; and the upper-right panel

![Circular Paths](image)

Fig. 11. The data of Experiment 3, parsed into four bins of instantaneous final gaze-heading angles. Although object-based sources of information all reliably predicted performance for the nominal data, only IM predicted the absolute data. For those stimuli without any object-based sources of information (Stimuli 000) only the data within bins of 3–6° and greater than 6° gaze-heading angle, were reliably above chance.

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Our observers generally met our performance criteria in Experiment 1 for linear paths (75 or 95% performance at 3.75° traveling at 2 m/s; Cutting, Springer, braren & Johnson, 1992; Vishton & Cutting, 1995). Performance, however, is generally lower for circular paths than for linear paths, but it is not clear one can develop appropriate accuracy criteria for curved paths. As a pedestrian one would not likely be on a curving path already before one had to negotiate a turn (Cutting, 1986).
Table 3
Performance at various gaze-heading angles for the eight types of experimental trials in Experiment 3 (N = 22)

<table>
<thead>
<tr>
<th>Trial type</th>
<th>Final gaze-heading angle</th>
<th>&lt;1.5°</th>
<th>1.5–3.0°</th>
<th>3.0–6.0°</th>
<th>&gt;6°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%N</td>
<td>%N</td>
<td>%N</td>
<td>%N</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>71 (17)</td>
<td>58 (49)</td>
<td>42 (24)</td>
<td>82 (73)</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>64 (53)</td>
<td>81 (98)</td>
<td>81 (19)</td>
<td>84 (293)</td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>53 (45)</td>
<td>71 (67)</td>
<td>61 (56)</td>
<td>75 (71)</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>60 (124)</td>
<td>67 (244)</td>
<td>69 (223)</td>
<td>75 (283)</td>
<td></td>
</tr>
<tr>
<td>011</td>
<td>29 (17)</td>
<td>86 (14)</td>
<td>65 (20)</td>
<td>78 (36)</td>
<td></td>
</tr>
<tr>
<td>010</td>
<td>70 (40)</td>
<td>70 (30)</td>
<td>73 (75)</td>
<td>90 (28)</td>
<td></td>
</tr>
<tr>
<td>001</td>
<td>44 (43)</td>
<td>56 (36)</td>
<td>59 (45)</td>
<td>81 (54)</td>
<td></td>
</tr>
<tr>
<td>000</td>
<td>47 (186)</td>
<td>56 (187)</td>
<td>64 (211)</td>
<td>68 (134)</td>
<td></td>
</tr>
</tbody>
</table>

*a The three digit codes for the stimuli are the same as in Table 1.

combines all three sources of information and shows a mean difference of 11%. As other analyses have shown, IM was the most potent source of information in these data; other sources diluted the effect of IM.

As in Experiment 1, the object-based sources of information were not correlated with one another (median r = 0.02). Also, as in Experiment 1, when performance was measured for each observer, then pooled across observers, it was above chance for stimuli without any of the object-based sources of information (Stimuli 000) when gaze-heading angles were between 3.0 and 6.0° (64%, t(21) = 2.30, P < 0.05, uncorrected for multiple comparisons), and also when the gaze-heading angle was greater than 6.0° (78%, t(21) = 4.29, P < 0.001). Thus, again, these data show our theory is incomplete. The bottom panels of Fig. 11 show the analogous absolute data for the 12 observers in Group 2. In a regression analysis on these data, there were only reliable effects of gaze-heading angle and IM (F(1, 1903) = 6.44 and 40.5, P < 0.001); there were no reliable effects of DDLO or OD (F(1, 1903) < 1). Indeed, the lower left-hand panel shows a difference in absolute heading between those trials with and without IM of 1.82°, but this difference erodes to 0.62° with the addition of DDLO, and is 0.70° with the addition of OD. Finally, consider differences for Group 2. As in the results of Experiment 2, there were considerable differences among individuals for the absolute data (F(9, 1910) = 11.6, P < 0.001), but not for the same data when analyzed in a nominal fashion (F(9, 1910) = 1.7, P > 0.05). Again, such a result suggests the nominal data are more stable, that the absolute data are subject to observer biases independent of their performance.

7.2.3. Inefficacy of field-based information

As in Experiment 1, there were no effects of differential motion, spatial pooling, or size-weighted spatial pooling, either in the nominal heading analysis (F(1, 3044) < 1.5, P > 0.15) or in the absolute heading analysis (F(1, 1903) < 1). Indeed, as shown in the upper panels of Fig. 12, nominal performance was slightly worse on those trials where differential motion predicted the heading direction (mean of −3% across the four bins, predicted minus unpredicted). Predictions were only slightly better for spatial pooling (mean of 1%) and size-weighted spatial pooling (mean of 4%).

The pattern was even less convincing for the absolute data, shown in the lower panels of Fig. 12: Differential motion, spatial pooling, and size-weighted spatial pooling slightly mispredicted observer’s heading judgments (overall means −0.43, −0.23 and −0.65°, respectively).

7.3. Overview

Our first investigation of information used during curved paths yielded results similar to those of previous experiments with straight paths. In particular, for these environments: (a) three sources of object-based information served as bases for the viewers’ judgments, although here IM proved more salient than DDLO or OD; (b) the addition of field-based information to the object-based sources did not improve performance. When all information was combined, the effect of IM was again the largest, followed by DDLO and OD; (c) the data were also consistent with our theory of information usage. The bottom panels of Fig. 11 show the analogous absolute data for the 12 observers in Group 2. In a regression analysis on these data, there were only reliable effects of gaze-heading angle and IM (F(1, 1903) = 6.44 and 40.5, P < 0.001); there were no reliable effects of DDLO or OD (F(1, 1903) < 1). Indeed, the lower left-hand panel shows a difference in absolute heading between those trials with and without IM of 1.82°, but this difference erodes to 0.62° with the addition of DDLO, and is 0.70° with the addition of OD. Finally, consider differences for Group 2. As in the results of Experiment 2, there were considerable differences among individuals for the absolute data (F(9, 1910) = 11.6, P < 0.001), but not for the same data when analyzed in a nominal fashion (F(9, 1910) = 1.7, P > 0.05). Again, such a result suggests the nominal data are more stable, that the absolute data are subject to observer biases independent of their performance.

Fig. 12. The data of Experiment 3, parsed into four bins of final-gaze-heading angle. Consistent means those trials correctly predicting the heading direction and inconsistent means those predicting the heading direction in the opposite direction. That performance is essentially the same means that none of the field-based sources of information predicted performance in this situation.
OD; (b) although performance was poor without any of these object-based sources it was above chance when gaze-heading angles were pooled within bins of 3.0–6.0° and above 6.0°; (c) none of the field-based schemes accounted for any significant variance in the viewers' judgment data; and (d) absolute measures were considerably more variable than nominal measures. Perhaps most interestingly in this stimulus context, observers seemed to have little ability in judging the future of their circular path. Instead, regardless of instruction, they reported their instantaneous heading.

The final experiment completes the conceptual design. We manipulated the three object-based sources of information in an orthogonal manner, as in Experiment 2, but using curved paths as in Experiment 3.

8. Experiment 4: heading direction from circular translation in a factorial design

8.1. Method

Ten observers participated in a laboratory setting, all with acceptable performance levels. Each viewed a sequence of 128 trials: eight configurations of object-based stimulus information × two sides of the circular path (looking in and looking out) × two sides of approach (left and right) × four replications. Only one circular path radius (150 eye heights) was used, and only one path-transit angle (4°). In addition, the same 122 classroom observers who participated in Experiment 2 participated here as well, after that task. They viewed a 32-trial sequence: eight configurations of object-based information × two sides of the circular path × two sides of approach, with only one token of each configuration and again only at a path-transit angle of 4°. Final gaze-instantaneous heading angles were 2.3 and 5.6°. Lab viewers made absolute path judgments, whereas those in class made nominal path judgments. Practice trials for the lab sequences involved linear path; those in the classroom involved circular paths. No trials dissociated path transit and final heading, so no analysis separating the two is reported here.

8.2. Results and discussion

8.2.1. Efficacy of object-based sources of information, but mostly IM

For the laboratory setting, overall data for the eight stimulus types are shown in the left panel of Fig. 13. The only reliable object-based information source was IM (F(1, 9) = 24.8, MSe = 7.0, P < 0.001), with mean performance 88% when it was present and 74% when absent. Neither DDLO or OD yielded reliable effects (F(1, 9) < 2.79, P > 0.10), although mean performances were 85 versus 77%, and 83 versus 78%, respectively for their presence and absence. Shown in right panel of Fig. 13 are the performances of the classroom observers on the eight types of stimuli. Here, in contrast to the laboratory data, there were reliable effects of DDLO, IM, and OD (F(1, 121) > 26.9, P < 0.0001); with performances of 82 versus 63%, 76 versus 69% and 77 versus 69%, respectively. Unlike Experiment 2, however, there were no reliable third-order interactions (F(1, 9) < 1; F(1, 121) = 3.29, P > 0.05); but as in Experiment 3, here in both the laboratory and classroom settings, there were reliable effects of looking into the circle versus looking out (86 vs 76% in the lab, F(1, 9) = 13.6, P < 0.005; and 79 vs 67% in the class, F(1, 121) = 23.6, P < 0.001). These latter effects are likely to be due to differences in the final instantaneous gaze-heading angles; although final path-transit angles were always the same, the final gaze-heading angle when looking into the circle was 5.6° and that when looking out was only 2.3°. Since performance in Experiment 3 was largely an effect of final gaze-heading angle, the considerably larger heading angle when looking into the circle is likely to have made these trials considerably easier. Finally, performance of stimuli without any object-based sources of information (Stimuli 000) was not reliably above chance in either the laboratory (F(1, 9) = 4.8, P > 0.05) or the classroom situations (F(1, 121) < 1).

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6 Some of the results for the laboratory subjects were also reported in a very different form in Wang & Cutting (1998).
8.2.2. Inefficacy of the field-based information

Again, regression analysis showed that differential motion, spatial pooling, and size weighted-spatial pooling accounted for less than 1% of the variance in the data in both the lab and classroom settings ($F(1, 1276) < 1.5$, $P > 0.20$; and $F(1, 1948) < 1$, respectively).

8.3. Overview

The results of Experiments 4 generally mirrored aspects of previous experiments. First, as in Experiment 3, IM was a more potent source of information than either DDLO or OD, but there was some evidence of viewers’ use of all three, as in Experiments 1 and 2. Second, as in Experiment 2, performance on the stimuli without the object-based sources of information was not reliably above chance. Third, as in Experiment 3, viewers performed better when looking inwards from the circular path than when looking out from it, a likely effect of differences in instantaneous gaze-heading angle. And fourth, as in all previous experiments, there was no evidence for the use of the three field-based pooling schemes.

9. General discussion: neurophysiological underpinnings and object-based heading information

Perhaps the most interesting and consistent pattern of results across the four experiments reported here is that of the difference in use between object-based and field-based information. We presented evidence in all four experiments that object-based sources of information were used for heading direction judgments, and that field-based information is not used. The result supports our Tenet 6, but is not consistent with many approaches in the literature (Rieger & Lawton, 1985; Heeger & Jepson, 1990; Hildreth, 1992; Perrone & Stone, 1994; Royden, 1994; Warren & Saunders, 1995). If our results and analyses are correct, why might this be?

There is ample evidence that visual system can pool motion over reasonably large regions of the visual field (Morgan & Frost, 1981; Williams & Sekuler, 1984; Allman, Miezis & McGuinness, 1985; Watamaniuk, Sekuler & Williams, 1989; Pasternak, Albano & Harvitt, 1990; Duffy & Wurtz, 1991; Blake, Cepeda & Hiris, 1997). For us, the question is whether humans do pool such motion in the context of everyday behaviors, such as heading determination during locomotion. We suggest not. Our view is that, since people look around at objects during locomotion (Wagner, Baird & Barbareis, 1981) and seem likely to be paying attention to them, there are likely to be downward effects of attention on the workings of neurons with such large receptive fields (Mountcastle, Motter, Steinmetz & Sestokas, 1987; Maunsell, Sclar, Nealey & DePriest, 1991; Motter, 1993). When observers attend to particular objects in the visual field, then, we suspect the activity of these neurons will be a function, not of the motion within the entire field, but of the motion of the attended object in that field. On the other hand, when observers (human or otherwise) are given a field of moving dots that blanket the receptive field, attention cannot typically be used to single out one of these dots, and thus the pattern as a whole dictates neural activity and what is perceived.

10. Conclusions

At least three conclusions can be drawn from the experiments and simulations reported in this article. First, and most importantly from our perspective, multiple sources of object-based information appear to be used by observers to make heading judgments, both when they are traveling on straight and on curved paths. For straight paths, the results of Experiments 1 and 2 showed evidence for the use of DDLO, IM, and OD. The methods in these experiments entailed regression and factorial designs, respectively. These results are a replication and extension of those of Cutting, Springer, Braren & Johnson (1992) and Cutting (1996). The results of Experiment 2 even suggested that these object-based sources are intersubstitutable, and that more than one source of information does not improve performance. For curved paths, Experiments 3 and 4 suggested that all sources were also used for judgments along curved paths, although the most potent source was clearly IM.

Second, there was no support in any of the four experiments that, in small forest environments, observers pool motion information across the visual field. In particular, neither differential motion (Rieger & Lawton, 1985: Rieger & Toet, 1985) nor spatial pooling (Warren & Saunders, 1995) accounted for any reasonable variance in the observers responses. It may be that these first two conclusions are confined to the sparse kind of environments investigated here, but we think not. Remember, from the simulations of the efficacy of the various object-based and field-based information sources, these sources will all be highly correlated in cluttered environments; each works nearly all the time. It is only in sparse environments that one can reasonably expect to tease them apart.

Third, and on a different note, we found two interesting relations between nominal and absolute responses by viewers. First, whether observers indicated their absolute heading or only the nominal direction of their heading (left or right of a fixation tree), the results analyzed in a nominal manner were not different from
one another. This suggests that the absolute task places no extra burden on nominal judgments. Second, we found no statistically reliable individual differences in nominal judgments, but consistently reliable differences in absolute judgments. These suggest to us that absolute judgments are open to various biases. We believe the heading judgments made by observers are best characterized as either ordinal (from comparisons across trials types) or nominal.

10.1. Coda

Two aspects of the results of these experiments leave certain matters unsettled. First, despite the goal set in our research principle, performance at some gaze-heading angles in some experiments remained above chance despite the absence of the three object-based sources of information. To be sure, when the data were sorted by instantaneous gaze-heading angles, we were able to account for the trends in performance on all but 783 out of 16,208 trials (or 5%), better than any of the current contenders. Nonetheless, our theory of heading judgments on the bases of DDLO, IM, and, OD is incomplete; we are currently focusing on a new approach to make good on our research principle of accounting for all the data (Cutting, Alliprandini, Creutz & Wang 1998; Wang & Cutting, 1998).

Second, in our discussions of these results with colleagues, we have found that the most controversial aspects of our approach are two emphases—first on nominal rather than absolute heading information, and second on ordinal rather than absolute heading judgments. Our beliefs are much stronger in the former than in the latter. We acknowledge that the absolute-response results presented here can be interpreted in at least an ordinal manner; that is, observers responses indicate greater perceived headings with greater gaze-movement angles. We also acknowledge the results of others, again showing at least an ordinal relation between judgments and true headings. In our view, however, nature of the apparent measurement scale of the response (the heading judgments) does not have to be the same as the measurement scale as that of the information. Here we appeal to a measurement-theoretic analogy with nonmetric multidimensional scaling (NMDS, see for example, Shepard, 1980). NMDS takes a matrix of ordinal judgments (say, the ranked distances between all pairs of a number of cities in Europe) and will convert them into a two-dimensional solution (a map) that will have near-metric qualities (the distances between the cities will roughly proportional). That is, with multiple constraints the information available from one measurement scale (nominal or ordinal) can be used to construct a representation with properties of a higher scale (in these cases, ordinal or interval). Thus, multiple nominal constraints that appear within or across pursuit fixations will foster responses that are increasingly accurate (Cutting, Alliprandini, Creutz & Wang, 1998; Wang & Cutting, 1998).

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References


