
Images, imagination, and movement: Pictorial representations and their development in the work of James Gibson

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Received 6 June 1999, in revised form 13 March 2000

Abstract. For more than 30 years James Gibson studied pictures and he studied motion, particularly the relationship between movement through an environment and its visual consequences. For the latter, he also struggled with how best to present his ideas to students and fellow researchers, and employed various representations and formats. This article explores the relationships between the concepts of the fidelity of pictures (an idea he first promoted and later eschewed) and evocativeness as applied to his images. Gibson ended his struggle with an image of a bird flying over a plane surrounded by a spherical representation of a vector field, an image high in evocativeness but less than completely faithful to optical flow.

“What can be said about ... the fidelity of pictorial representation ... ?

[Pictures] make perception effortless by approximating the natural kind of perception.”

Gibson (1960, page 226)

1 Introduction

The study of how we see, and how we understand what we see, is an ancient discipline. The traditional field of optics is, quite simply, about visual perception. Well-exemplified by the work of Euclid in the 3rd century BC (Burton 1945), Alhazen in the 10th century AD (Sabra 1989), Descartes in the 17th century (Smith 1958), and Helmholtz in the 19th century (Helmholtz 1866/1925), works on geometric optics and visual perception almost always use visual images as a descriptive aid. It is intriguing that the use of images is nearly obligatory in explaining how we see; sounds, smells, tastes, and rubbings seem less necessary to the explanation of our hearing, olfaction, gustation, and touch. In scientific documents, the use of images entails a reflexive process on the part of the viewer and reader of the text: One must use vision to understand vision, must peruse an image to imagine better how we look at the world, and must learn to see in a picture how we see in real life. In the context of the scholar and scientist of vision, prose and reflection have clearly been insufficient for more than twenty centuries; and, indeed, so is looking directly at the world around us. Instead, in the study of vision we must often look at an image of the world, and even at a schematic image of ourselves looking at the world; then the vicarious experience informs us about the direct experience.

James J Gibson, often argued to be the most important perceptual theorist of the 20th century (Nakayama 1995; Neisser 1990; Reed 1988; Restle 1980), wrote extensively about many topics in perception, particularly visual perception. He, too, used many visual images to present his view of how we see, and the focus of this essay is the development over a thirty-year period of his representations of motion as experienced by a moving observer. At the same time, however, Gibson also wrote extensively about the perception of pictures. Although Gibson never wrote about pictures in scientific documents, we can read his statements about pictures to inform ourselves about his thoughts during the development of his representations of movement.

For example (as suggested above) Gibson believed that, because of the “fidelity of pictorial representation”, the close relationship of the layout of the picture to that of the

pictured, these images could be used to “help satisfy [our] curiosity about the world”. Be they photographs, paintings, line drawings, cartoons (all of which Gibson studied), or scientific representations (which he did not), pictures “convey knowledge of a sort. They make perception effortless by approximating the natural kind of perception” (Gibson 1960, page 223). By their use and through their fidelity an author/image maker allows his or her reader to have “an almost direct acquaintance with things” (page 223) and by extension the important concepts in a scientific domain. What is clear is that the concept of fidelity, which Gibson espoused for more than a dozen years during his struggle with representations of movement, only later to eschew, is both characteristic of science in general and central to any understanding of his images.⁽¹⁾

2 Optical flow and the tension between evocativeness and fidelity

What does the world look like when we move through it? Of course, one has the impression of speed, the impression that one is moving and not the environment, and perhaps even the impression of breathlessness. Nonetheless, it is difficult to put into words exactly what the world looks like when one moves. If one were to try to describe, without arms, the flow of movement around oneself to someone not completely sure about what was being discussed or why, one would have difficulty. Such is the problem of representing optical flow.

There have been many visual representations of optical flow in the scientific literature over the last fifty years. Consider a recent one from a popular textbook by Goldstein (1999) in figure 1. Brown and Deffenbacher (1979), Bruce et al (1996), Coren et al (1999),

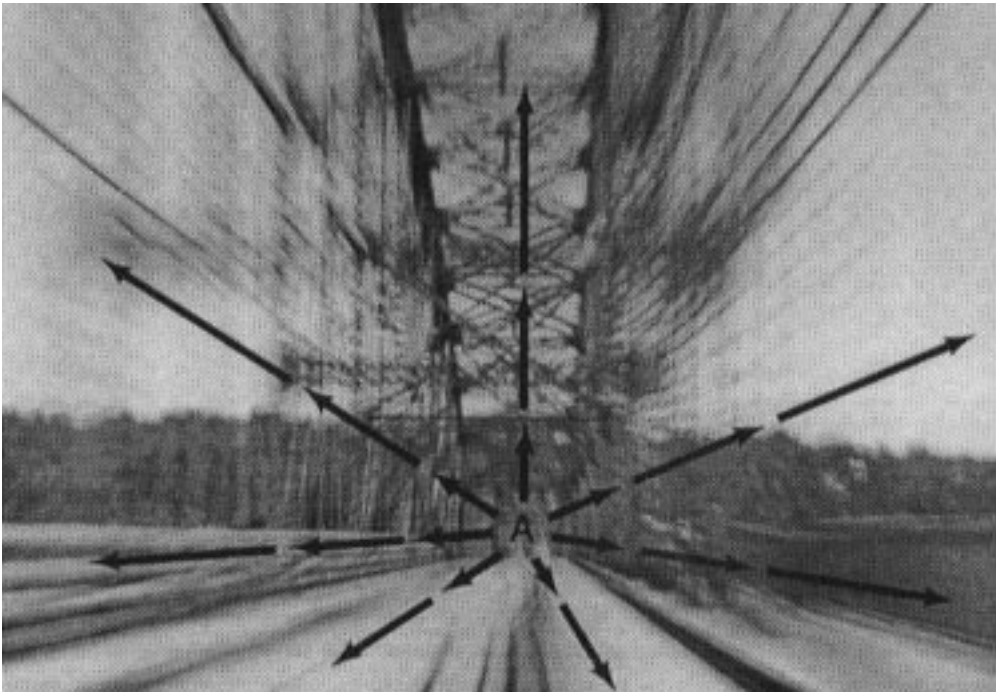


Figure 1. A textbook illustration of optical flow and the motion it evokes (Goldstein 1999). Reprinted with permission of the author and publisher.

⁽¹⁾ For Gibson, “the fidelity of a picture can be defined as the degree to which its surface sends the same sheaf of [light] rays to its station point [where the observer might be located] that is sent to a certain fixed station point at the scene represented” (Gibson 1960, page 223). Theories of the relation between a picture and the depicted are, of course, myriad. For other perspectives, see Gombrich (1982), Goodman (1968), Ittelson (1996), Mitchell (1986), and Schier (1986).

Hershenson (1999), Matlin and Foley (1992), and Palmer (1999) have used similar, if more schematic, images. When taking this picture, the motorist and photographer traversed a bridge at some speed. From the image one has the impression of an outward flowing movement—more rapid nearby, slower in the distance—completely enveloping the car. This impression is represented by the modest blur and by the vectors (arrows) of different lengths (velocities) superimposed on it. Notice that all vectors point away from where one is headed, marked by the letter A superimposed over the opposite end of the bridge. This representation is evocative, which was its intent, but can we ask more? Is it faithful in representing the amount of motion as it occurred? To assess such fidelity we must ask: To which parts of which struts and crossbeams of the bridge does each vector attach? Since no answer is possible, we cannot press this representation further; its purpose is evocation, not fidelity.

One of the goals of science is accuracy of representation, whether in depicting numerical or graphical representations of data, in reporting the methods of an experiment or observation, or in citing other sources. Gibson's early notion of fidelity of pictures is particularly in tune with this idea. A scientific image, as a picture of data or conceptualization of a phenomenon under study, must be faithful. For Gibson (1960, page 223), "functional fidelity ... is simply the degree to which the variables to which the eye is sensitive are the same in one array as the other. Complete fidelity of [this] ... sort is achievable". Applied to the study of motion, then, we have the following: Since the eye is sensitive to motion, and since vectors can be used to represent that motion, the relative velocity of any particular point in the optical array ought to be represented by a vector in the picture whose length corresponds to that velocity. "Fidelity of form and proportion in a static picture entails that the perspective be 'correct'" (Gibson 1960, page 223). But how do we ensure this perspective is correct? What format do we choose? How do we represent that format? These are the issues that haunted Gibson for a long time.

3 Four stages in Gibson's struggle with fidelity and the representation of optical flow

Over the course of the last 35 years of his career, Gibson investigated optical flow and the questions it raises. For example, when we are moving forward—walking, running, or riding in a car, boat, or airplane—how do we know where we are going? How do we know that we are moving and not simply the environment? How do we maintain balance while moving ahead? These questions are important and many subsequent researchers have tried to elaborate answers (eg Cutting 1986; Lee 1980; R Warren and Wertheim 1990; W H Warren 1998a, 1998b). The purpose of this paper, however, is not to try to answer these questions, but to trace the stages through which Gibson addressed them in a succession of representations (scientific images). He used these to teach himself and others about the problems connected with the perception of self-movement.

Gibson successively honed his images for the purposes of improving their impact and understandability. Initially, he seems to have decided that he needed two generally complementary sets. The purpose of one set was the evocation of self-movement, picturing the array of sensory impressions of a moving observer for a scientific audience in the manner of Goldstein's image (figure 1). This set, however, did not adequately represent 'the variables', in this case the vectors, to "the degree ... the eye is sensitive"; it did not send "the same sheaf of rays" to the viewer "that is sent ... at the scene represented" (Gibson 1960, page 223). Thus, a second set was needed. The purpose of a second set, I claim, was fidelity to the velocity field; to create an accurate scientific image.

3.1 *Evoking motion and invoking math: A tension in two dimensions*

During World War II Gibson served in the US Army Air Force with the task of trying to understand how pilots fly on the basis of what they see, without instruments. From this experience he produced a book (Gibson 1947). As a government publication it had limited circulation, but in it were the first scientific images of self-movement. The first of the set, seen in figure 2a, depicts the flight of a pilot and aircraft over a landing field.

Figure 2a surely served as the impetus for Goldstein's display (figure 1), and was composed fifty years earlier. The image has been popular in the literature: Bruce et al (1996), Gordon (1997), and Warren (1998b) have reprinted it, and Gleitman (1995) copied it. It represents a flyby; the pilot is passing over the airfield, without attempting to land. We know this because all the vectors in the vector field point from [or following Gombrich (1972, page 187), they "act like negative arrows" with respect to] a position on the horizon, not from the landing area on the airfield itself. A landing is depicted

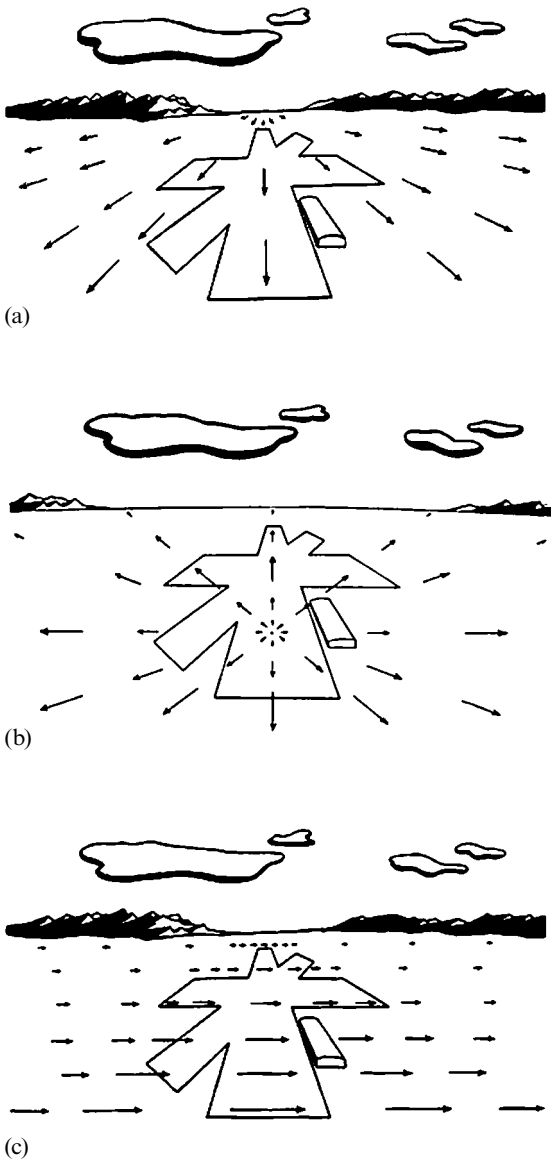


Figure 2. Three of Gibson's earliest images of optical flow (Gibson 1947, public domain). These depict (a) a flyby over the landing field, (b) a landing, and (c) a flyby to the left, opposite the flow vectors. All three were reprinted in Gibson (1950), but never again used by him.

in figure 2b. This second figure has been reprinted (Reed 1988; Schiff 1980) or copied (Hochberg 1978) less recently, and perhaps less often, than the flyby. The image in figure 2c is similar to both but represents what occurs when the pilot is looking to the side, in this case over the right shoulder as the plane flies in the direction beyond the left edge of the page. It seems not to have been reprinted. The relations among vector lengths in none of the three images are mathematically faithful to the situation, although those in the third figure are closer than those in the first two. Nonetheless, like Goldstein's image, the vector fields are reasonably successful in giving one the impression of one's own movement through the world.

Gibson, however, was not completely pleased with such images. Although they evoked locomotion, he must have felt the further necessity of fidelity to the velocity field. Consider his first attempt, shown in figure 3. It tries to represent what might be seen by a pilot looking (if he or she could) straight down to the ground beneath while flying towards the top of the page. The longest vector is in the middle and represents the flow directly underneath. Note that the vector size diminishes in all directions, although all vectors are parallel and point in the same direction. The top of the image indicates the horizon in front, the bottom the horizon in the rear, and the sides of the page the horizons to the left and right.

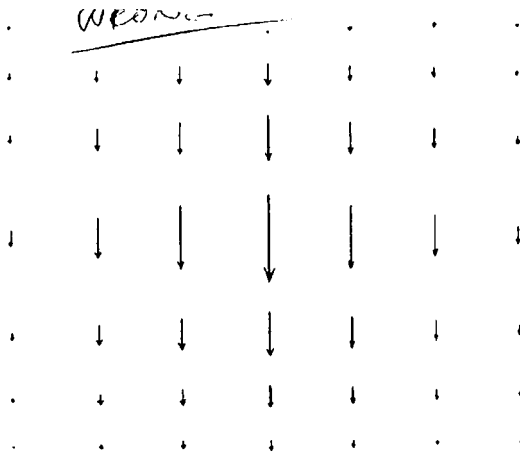


Figure 3. Gibson's first attempt at a mathematically accurate representation of optical flow, from Gibson (1947, public domain). This image was never reproduced in later works.

Figure 3 also has a handwritten inscription "wrong" in the upper left. Since this image was taken from one of Gibson's personal copies of his 1947 book, the annotation suggests he was not happy with this representation, although we do not know when his dissatisfaction began. Mathematically it does not follow convention. To an individual standing on, or flying over, a flat plane the horizon is best thought of as a series of points equidistant from one's current position. Thus, it should be a circle rather than a rectangle. But one suspects that something more than this mathematical inappropriateness was nagging Gibson. The evocative success of one set of images (figure 2) was greater than the mathematical success of the other (figure 3), but in retrospect neither was as great as he wanted.

3.2 *Evoking motion in three dimensions: Still far from fidelity*

Three years after the appearance of his wartime research, he published a second book (Gibson 1950), regarded by many researchers as one of the most important books on perception in the 20th century (Boring 1952; Hochberg 1990). In it Gibson reshuffled some of the material in his previous book, but added a sweeping overview and breathtaking overhaul of the field. Rife with photographs, it copiously used conceptual illustrations of many kinds. When discussing optical flow Gibson was sufficiently satisfied with some of his earlier evocative images (figures 2a, 2b, and 2c) to reprint them,

but he did not attempt to show a mathematical representation. The fact that he did not reprint figure 3 suggests that he was displeased with it within three years. But it also seems that Gibson was also not completely happy with his evocative images, because he added another, shown in figure 4. Here we see the foreshortened representation of a man seen from above and in front at a height of about 4 m. Two lines stretch out towards the horizon from his eyes, indicating binocular lines of sight (all other Gibson representations imply monocularly). The man is stationary but movement is represented on a sphere around him, with solid-line vectors in front (representing the general flow lines of objects he could see) and dotted-line vectors in back (representing those of the unseen). The ellipse represents a circle around the man oriented in the frontal plane.

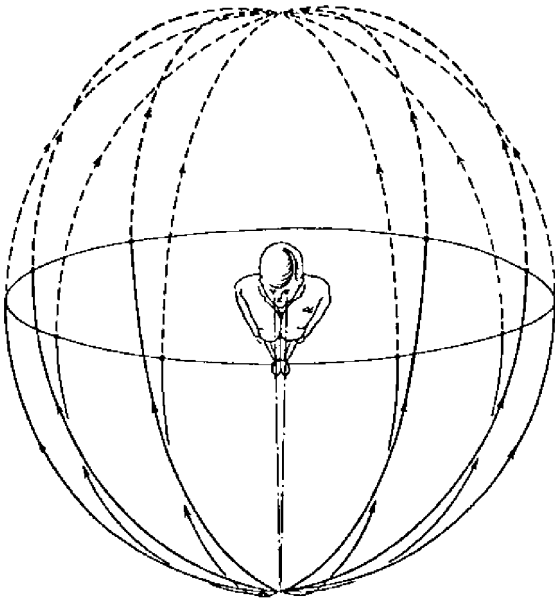


Figure 4. Gibson's (1950) image evoking the three-dimensional character of optical flow. There is no attempt at mathematical accuracy; it is for evocational purposes only. Gibson never used it again. Reproduced here with permission of Eleanor J Gibson.

Why is the man standing still, feet together, and yet the vector field indicates his movement? Despite this representational lapse, the use of a projection sphere around the observer is precisely the most appropriate mathematical convention for optical flow. On this sphere is represented the optical flow projected to a moving point, occupied by the eye of the observer. Thus, as a beginning, this conception is prudent but the image is incompletely satisfying.

In this image, almost certainly for the first time in the scientific literature on perception, we find a double-projection technique. The first projection surface in any image is the picture plane, or Alberti's window (Hagen 1986). It is through this window that one looks at the world as composed by the artist or illustrator. A second projection surface was occasionally used in Renaissance paintings, as in Jan van Eyck's *The Arnolfini Marriage* [1434] and Diego Velasquez's *Las Meninas* [1656]. In the former painting (the first projection surface, Alberti's window), one can see a spherical mirror (the second projection surface), which has the reflections of the witnesses to the wedding (Cole 1992; Comar 1992). Here in figure 4, Gibson used the same technique in that the flow of objects in the man's environment is projected onto the sphere (the second projection surface) and represented as a set of vectors, then projected again to the image plane (the first projection surface, delimited by the bounds of the figure) and to the viewer, the reader of Gibson's book. This technique is important for Gibson's later work, but he was apparently not satisfied with this image either. Although he was actively interested in optical flow for almost 30 more years, he never used it again.

3.3 Invoking math and flattening space: Fidelity at the cost of imagination

In 1950 Gibson did not try another mathematical representation, and he probably felt that he could not do justice to the problem alone. Thus, he enlisted two colleagues after he had arrived at Cornell University, Paul Olum (a mathematician, and later president of the University of Oregon) and Frank Rosenblatt (a psychologist and engineer who built the first perceptron pioneering neural network model for pattern recognition). In their collaboration, Gibson rectified the problem in 1947, and its absence in 1950, of a proper mathematical image of optical flow. Consider their fruits in figure 5 (Gibson et al 1955).

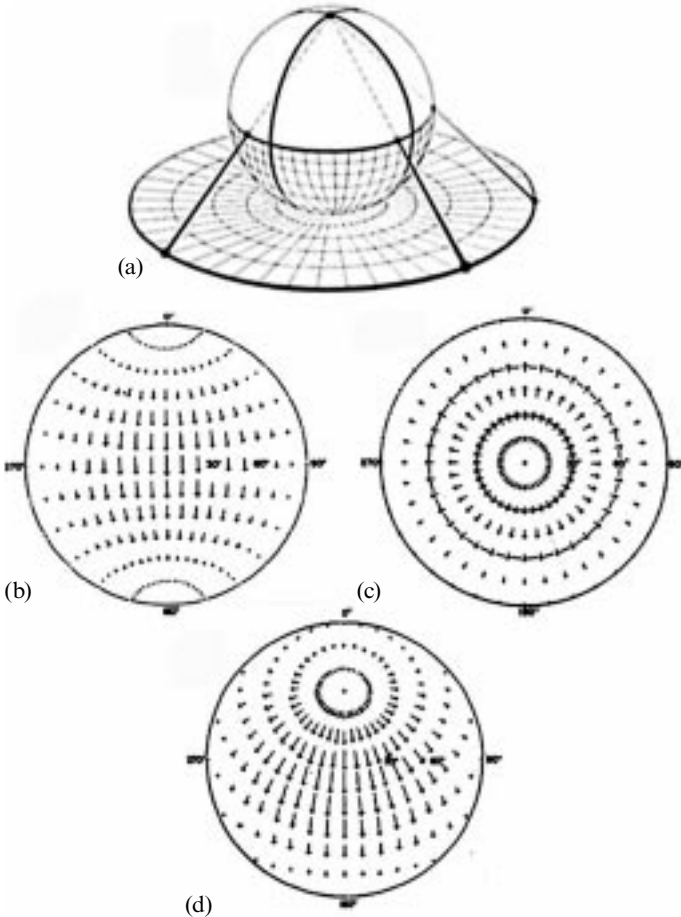


Figure 5. (a) The stereographic mapping process (adapted from Ikeuchi and Horn 1981) and three conformal maps of optical flow from Gibson et al (1955). They represent the flow seen when (b) flying over a terrain parallel to the ground, (c) directly descending, and (d) descending at a 45° glide slope (bottom). Each of these images is mathematically accurate, but not evocative. Panel (b) was reprinted in Gibson (1966, 1979), but the others were not. Panels (b)–(d) reprinted with permission of the University of Illinois Press.

These are almost wholly indigestible images to anyone without some mathematical training. They are, however, important precursors, so let me offer several guidelines as to how to approach them. Figure 5b is like figure 3; it represents what would be seen flying in the direction of the top of the page and again looking down. The flow pattern beneath the eye is from a flat terrestrial plain that stretches to the horizon on all sides. Second, the horizon is represented as a circle, correcting the inappropriateness of the

square in figure 3. Third, on the perimeter of the circle, the symbol 0° represents directly ahead, the direction of motion; 90° is directly to the right; 180° is directly behind; and so forth around the horizon. Notice again that the vector in the middle of the circle (directly beneath the pilot) is the longest (representing the fastest motion, just as in figure 3). Fourth, however, notice that the vectors are not parallel throughout the image; they fan out from the 0° , become essentially parallel along the horizontal meridian; and then compress and focus inward to 180° . What is this representation? What is this curvature about?

The most difficult aspect of this mathematical representation is that it is a stereographic projection, or, more generally, it is conformal (Snyder 1993); it flattens a curved surface so that it conforms to a plane. Figure 5a suggests how this is done. It yields many distortions in the represented space if one were to construe it, as viewers usually do, as Euclidean. Conformal displays are now more common in science and are perhaps most often used to represent regions on the surface of the brain (eg Maunsell and Newsome 1987; Van Essen 1985); in 1955, however, they were not.⁽²⁾ In Gibson's case the hemisphere beneath the eye (and beneath the man in figure 4) is flattened onto a circle. This is hinted at in the image, where the markers 30° and 60° line up with the 90° marker to the right. These are angles below the eye: 0° is the location of the longest vector, the 30° marker indicates an angle of 30° out to the right side from directly beneath the eye; similarly for the 60° marker; and the 90° marker (at the horizon) is at right angles to the point directly below. Finally, consider the pattern of the lateral arrays of vectors, bowing upward at the top of the figure, lying horizontally at the middle, and bowing downward at the bottom. These arrays, when mapped back onto objects on the planar surface, would lie on parallel stripes orthogonal (at right angles) to the direction of motion. With all these hints, which take about 10 minutes to explain in the classroom, I have found that students can reasonably digest, or at least accept, this image as a representation of optical flow. Their comprehension, however, remains largely an intellectual exercise; the image is still not grasped immediately and intuitively. Thus, the image is mathematically faithful to optical flow, but not evocative.

Gibson et al (1955), however, did not stop with a representation of horizontal flight over a plane. Figure 5c is a representation that might be drawn for a helicopter making a vertical landing on a planar surface. Notice that all vectors point away from the landing spot (the direction one is headed, sometimes called the aimpoint), and that the longest vectors form a ring 45° around it. I have found that students, with a bit of tuition, can also grasp this figure. Except for the changes in vector length as one moves out from the aimpoint—zero to relatively large to zero again—this image seems quite digestible and not unlike that of Goldstein in figure 1.

However, the final image seen in figure 5d is extremely difficult to grasp correctly. It is the same type of conformal mapping, but for the case of a 45° glide slope approach of a helicopter landing on a plane. There is a sense in which it is halfway between the other two, the first flying parallel to the plane and the second descending directly to it. The problem is that this image is almost universally misread. Indeed, Reed (1988) reprinted it to show this difficulty and to demonstrate, according to him, the complete inappropriateness of point projection techniques to discussions of real-world perception. Figure 5d is generally seen as an outward protruding globe, with a north pole at the singularity (the point of zero vector length), vectors aligned as latitudes around it, and as if something coated the globe and were dripping south. The representation is mathematically accurate and also evocative, but evocative in ways almost certainly alien to the intent of the authors.

⁽²⁾ In map making, conformality has been around since the 16th century, particularly in the Mercator projection (see Steers 1927). But it too has been problematic, for example in representing Greenland as slightly larger than South America when in fact it is only one-eighth the size.

3.4 Evocations and invocations in three dimensions: Fidelity 'through' imagination

It is unclear how satisfied Gibson was with these illustrations. He continued to write about the visual information in support of locomotion. He reproduced the first of the 1955 images (figure 5b) in his third (Gibson 1966) and last books (Gibson 1979; see also Reed 1988). In 1966, however, he also produced his most successful image of optical flow, shown in figure 6a. This image represents a bird flying over a plane, with the suggestion of a furrowed field. I call it the bird in flight. It is an exquisite scientific illustration, masterfully composed by Gibson himself (E J Gibson, personal communication). Gone are the indigestible conformal maps of 1955 (figure 5), but maintained are their hemispheric representations beneath the moving observer and their parallel arrays of vectors. Also gone are the streamlines of 1950 (figure 4), but embraced are its spherical projection surface and double-projection technique. What is new is that the separate vectors are projected onto the hemisphere (actually a quarter of a sphere for purposes of clarity) for us to see.

Students and scientists almost immediately grasp this image. Unpacking the structure beneath it, however, is not completely trivial. To help, I have added an illustration, in figure 6b. It is a head-on display of the bird also showing the eye of a virtual reader of the image. It shows the rays of light from the plane beneath the bird projected to

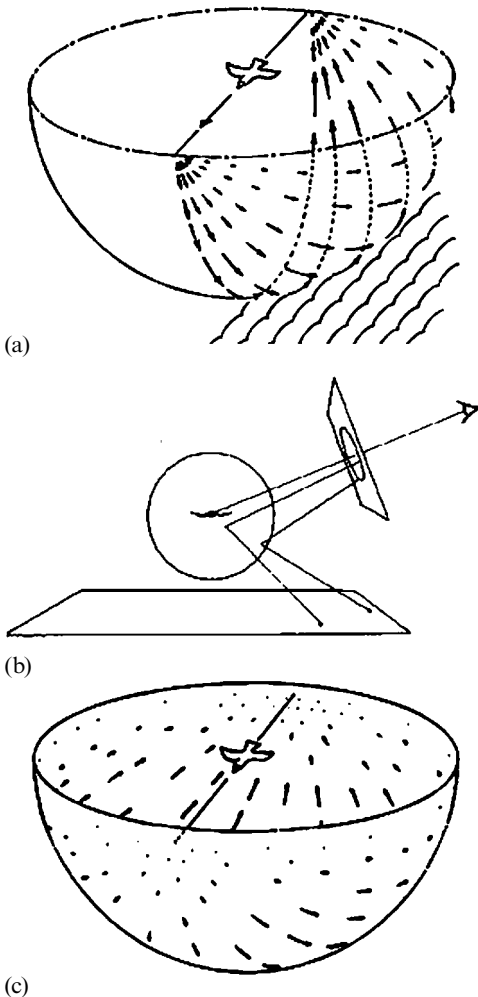


Figure 6. (a) Gibson's (1966) image of the 'bird in flight', evoking motion through space and thought by many to be mathematically accurate. It was also reprinted in Gibson (1979). (b) A representation of the physical situation of this double-projection technique. The combined image is from Cutting (1986), reprinted with the permission of MIT Press. (c) A computer recalculation of Gibson's bird in flight, adapted from Cutting (1986). Notice the difference in the length of vectors in the general direction of the bird's heading here as compared to the image in the top panel.

its eye, reaching the sphere around the bird, bouncing off and then projected to a picture plane (the image itself) and through to the simulated reader's eye. Not shown is the fact that the bird is moving, creating the vector field, and thus the reader of the image is also likely to be moving with the bird, perhaps on a parallel course. With the aid of this pedagogical image I have found that students can understand intellectually what they grasped immediately by intuition in the bird in flight.

3.5 *The impact of the bird in flight; and to what is it faithful?*

The success of Gibson's final image of optical flow is indisputable. It is widely recognized. It has been reprinted (eg Kelso 1995; Marr 1982; Reed 1996) or copied (eg Turvey 1990; Turvey and Carello 1986) in books and articles; in various forms it often appears on internet web pages and at conferences on title slides. Indeed, it belongs firmly within the canon of 20th century perceptual images. It is a symbol of Gibson, his later corpus of work, and the ecological approach. As powerful and evocative as the image is, however, one must nonetheless ask if it meets Gibson's earlier demands for fidelity for a picture? Interestingly, the answer is no. Admirable and simple as the image appears in composition, the hand calculations needed to render the vectors in their appropriate lengths are tedious in the extreme, and may have never been undertaken. Fortunately, computer-graphic techniques render almost trivial the computational problem of drawing the appropriate vector field projected on a sphere.

Consider such an image, shown in figure 6c. Scrutiny of figures 6a and 6c is necessary to discern their differences, but finding them repays the reader because they are theoretically essential. The images have in common the bird in flight, the hemispherical vector field around the bird, and a pair of polar loci, one directly ahead from which all vectors originate and the other directly behind towards which they point. But compare the magnitudes of the vectors near the forward locus, often also called the focus of expansion. In Gibson's figure they are much larger than in the computer-generated image; indeed, they are often an order of magnitude larger than they should be. This difference is critical to perceptual theory. In Gibson's view, the vectors in the optical flow field are said to reveal the locus of the aimpoint, as seen in figure 6a. In his representation the vectors relatively near the aimpoint are patent, and they clearly originate from the aimpoint. In the computer-generated figure, however, all vectors within 15° to 25° of the aimpoint are miniscule and it is difficult to discern their origin.

Why did this deviation from fidelity occur? Was Gibson less concerned with fidelity in 1966 when he produced the bird in flight?⁽³⁾ An answer to the latter query comes from his later work on picture perception. He later described the development of his views after 1960, and his rejection of the concept of fidelity (Gibson 1971, pages 28–29):

“There is still another objection to the ... definition of fidelity in terms of light-rays and the form they project... It does not apply to caricature... A caricature may be faithful to those features of the man that distinguish him from all other men and thus may truly represent him in a higher sense of the term.”

In this manner, Gibson set aside fidelity as a direct mapping of the magnitude of object displacements to vector rays. He released himself, probably in the mid 1960s and at the same time he first published the bird in flight, from the necessities of trying to show a mathematically correct representation of optical flow. Thus, I would claim, the bird in flight should be interpreted as an evocative representation and faithful to optical flow only ‘in a higher’ (and undefined) ‘sense of the term’. It is a caricature.

⁽³⁾ Gibson (1966, chapter 11) offered a lengthy discussion on the perception of pictures, but he failed to use the term fidelity, as he had in his two previous writings on pictures (see Gibson 1954, 1960). Thus, it seems that in 1966 he was not satisfied with the term; but only overtly denounced later, in Gibson (1971).

Yet it may be the evocative power of such illustrations in science that causes students and other scientists not to question them. From another context in his research and as cited above, Gibson suggested that perhaps the impact of images can be so forceful, they “leave nothing to the imagination, perhaps they stultify it. They might be said to encourage passivity rather than activity” on the part of the reader (Gibson 1960, page 225). Perhaps once such images become part of the canon of a discipline, one has difficulty imagining that the truth be another way.

3.6 *Coda on wayfinding*

The major point of this paper has not been to discuss perceptual theory. Instead, it has been to discuss the conceptualization, the long-term development, and then the impact of a compelling and important scientific illustration. Nonetheless, as a result of this discussion one might wonder: How does one find one’s way if not by the radial expansion of optical flow around the aimpoint? On the basis of figure 6c, we would surely have to integrate the motion information over a long period time, or over a large sector of the visual field. Yet laboratory studies by those who support Gibson’s view (eg Kim et al 1996; Warren et al 1988) show that neither is necessary. Thus, something seems amiss. Indeed, there is considerable debate in the literature on how pedestrians really find their way (eg Cutting 1996; Cutting et al 1992; Kim et al 1996; Lappe et al 1999; Royden et al 1992; Stone and Perrone 1997; Warren 1995, 1998a).

Most studies of heading perception have used moving fields of dots as stimuli. Such a technique is eminently defensible on grounds of isolating motion from other sources of information, but it is one that Reed (1988, 1996)—Gibson’s biographer—argued was inimical to Gibson’s point of view. There are also empirical reasons to question the use of such stimuli (Vishton and Cutting 1995; Cutting et al 1997). Dot fields often yield different results than more structured, naturalistic stimuli in situations with the same parameters; they seem to induce artifacts, response biases, and even different percepts—such as perceived path curvature during pursuit fixations off one’s path when no path curvature exists. Many studies have also presented stimuli out of scale with pedestrian movement: they either have optical velocities faster than those achieved on foot, or (because speed and distance scale with one another) present objects (dots) so close to the observer that they could not be avoided. Results of such studies may be pertinent to automobile safety, but not likely to the pedestrian constraints under which our visual system evolved.

These images of optical flow developed by Gibson portray only the motion around a moving observer. What the observer’s eyes happen to be doing was not generally considered.⁽⁴⁾ The assumption of a nonmoving eye is prudent for many animals. Most birds (as in figure 6a) do not typically move either their eyes or their head when they fly, unless they wish to turn; indeed, many birds do not even have spherical eyes and cannot move their eyes independently of their head under any circumstances. Thus, Gibson’s assumption of unmoving eyes is appropriate for his bird in flight, perhaps even motorists, but not for pedestrians.⁽⁵⁾

⁽⁴⁾ Gibson (1950) produced one image (page 125) implying eye movements, but did not reprint it. In it the observer looked to the side in mid-distance, as if on the train. Foreground vectors show motion in one direction; background the opposite. This image was reprinted by Levine and Shefner (1981), copied by Brown and Deffenbacher (1979) and Sekuler and Blake (1994), and discussed in detail by Cutting (1986, pages 186–190).

⁽⁵⁾ Calvert (1954, page 240), suggested “when a cinematographic film is taken of the face of a driver of a vehicle starting from rest, it is found that he scans the visual field only when the vehicle is moving slowly. As the speed increases, the driver scans less and less, until finally he begins to stare fixedly in the direction in which he wishes to go, usually at his aiming point if he can see it.” For a contemporary analysis of this pattern see Land and Lee (1994).

Studies of pedestrian eye-movement behavior show that people spend little time looking near their heading (Wagner et al 1981); in fact, we look within 5° of our heading less than 10% of the time. Nonetheless, Cutting et al (1992) estimated that we, as pedestrians, need to know where we are going within 3.5° . Given that personal safety, and ultimately the viability of our species, dictates that we must have accurate heading perception, the information we use for heading detection must lie off our path, not on it or at the end of it (Gibson's focus of expansion).

When we move through any environment at accustomed speed, we look around, picking up information with our foveae and avoiding blur (Land 1999). We typically pick out something to look at, and follow it with our eyes as we move forward. This is called a pursuit fixation. We then quickly glance back (saccade) generally in our direction of movement, completing what is called the optokinetic reflex (Hoffman 1986). Over time, we repeat the sequence, looking slowly left then quickly right, right then left, down then up, and so forth, as we walk. Pursuit fixations create two types of flow, one like that in figure 6c, and another uniform at any latitude orthogonal to the axis of eye rotation. Schemes have been developed for decomposing the two flow fields (see Warren 1995), but I have found them unconvincing (Cutting et al 1992, experiment 8). We found that some flows, similar to but simpler than those of natural gait, yield results considerably worse, thus suggesting they are undecomposable. If simpler flows are not decomposed it would seem none is.

Instead, a different scheme seems likely: While moving forward and looking within 45° of our path—where we spend 90% of our looking time (Wagner et al 1981)—we take advantage of the relative motion of objects around where we are looking. These have one of three characteristic patterns: Objects converge towards one another, they decelerate apart, or they accelerate apart (Cutting 1996; Wang and Cutting 1999), and fixation on one member of such pairs makes the relative motions easier to register. Pairs in the first two categories yield unambiguous information about heading: It is always to the outside of the nearer member of a pair that is converging or decelerating apart. These are, in the spirit of Gibson, invariant pairs—there is an invariant relation among the observer, the pair of objects, and heading that is independent of translational velocity. The latter kind of pair—those with objects accelerating apart—yields only probabilistic information. Wang and Cutting (1999) calculated that heading is to the outside of the far member or the pair 69% of the time, between them 23%, and to the outside of the near member 8%; thus, we call it a heuristic. We have found that observers look more often at members of invariant than heuristic pairs (Cutting et al 2000), and this makes sense. They offer information about heading that is surer. We also found that observers looked less often between members of invariant than heuristic pairs, and this also makes sense. Heading can never lie between members of an invariant pair.

Nonetheless, the information offered by an invariant pair is nominal, not absolute. That is, these invariants specify information about heading, left or right of a given landmark, but not how far left or right. The key to accurate heading assessment, however, is found in the coupling of several invariants, particularly any two such pairs that may exist on either side of the heading. With such pairs of opposite sign, heading judgments have a mean accuracy within 0.8° , even in environments with only four trees (Wang and Cutting 1999).

Acknowledgements. This article is based on a presentation at the 5th conference of the Académie du Midi, 'Imagination and Cognition,' in Tuchan, France, in June 1993, and subsequent lectures at the Université de Genève in March 1997, and the University of Pennsylvania in November 1999. The work was supported by a John Simon Guggenheim Memorial Fellowship and by National Science Foundation Grants SBR-9212876 and ASC-9523483. I thank James Ferwerda, Jean Lorenceau, and Peter Vishton for their assistance; and Eleanor J Gibson, Nan Karwan, Manfredo Massironi, Nicholas Wade, and an anonymous reviewer for their comments.

References

- Boring E G, 1952 "Visual perception as invariance" *Psychological Review* **59** 141–151
- Brown E L, Deffenbacher K, 1979 *Perception and the Senses* (New York: Oxford University Press)
- Bruce V, Green P R, Georgeson M A, 1996 *Visual Perception: Physiology, Psychology, and Ecology* 3rd edition (Hove, Sussex: Psychology Press)
- Burton H, 1945 "Euclid's Optics" *Journal of the Optical Society of America* **35** 357–372
- Calvert E S, 1954 "Visual judgments in motion" *Journal of the Institute of Navigation* **7** 233–251
- Cole A, 1992 *Perspective* (London: Dorling Kindersley)
- Comar P, 1992 *La perspective en jeu* (Paris: Découvertes Gallimard)
- Coren S, Ward L M, Enns J T, 1999 *Sensation and Perception* 5th edition (Fort Worth, TX: Harcourt Brace)
- Cutting J E, 1986 *Perception with an Eye for Motion* (Cambridge, MA: MIT Press)
- Cutting J E, 1996 "Wayfinding from multiple sources of local information in retinal flow" *Journal of Experimental Psychology: Human Perception and Performance* **22** 1299–1313
- Cutting J E, Alliprandini P M Z, Wang R F, 2000 "Seeking one's heading through eye movements" *Psychonomic Bulletin & Review* in press
- Cutting J E, Springer K, Braren P A, Johnson S H, 1992 "Wayfinding on foot from information in retinal, not optical, flow" *Journal of Experimental Psychology: General* **121** 41–72
- Cutting J E, Vishton P M, Flückiger M, Baumberger B, Gerndt J, 1997 "Heading and path information from retinal flow in naturalistic environments" *Perception & Psychophysics* **59** 426–441
- Gibson J J (Ed.), 1947 "Motion picture testing and research", Report No 7, Army Air Force Aviation Psychology Program Research Reports (Washington, DC: US Government Printing Office)
- Gibson J J, 1950 *Perception of the Visual World* (Boston, MA: Houghton Mifflin)
- Gibson J J, 1954 "A theory of the perception of pictures" *Audio-Visual Communication Review* **1** 3–23
- Gibson J J, 1960 "Pictures, perspective, and perception" *Daedalus* **89** 216–277
- Gibson J J, 1966 *The Senses Considered as Perceptual Systems* (Boston, MA: Houghton Mifflin)
- Gibson J J, 1971 "The information available in pictures" *Leonardo* **4** 27–35
- Gibson J J, 1979 *The Ecological Approach to Visual Perception* (Boston, MA: Houghton Mifflin)
- Gibson J J, Olum P, Rosenblatt F, 1955 "Parallax and perspective during aircraft landings" *American Journal of Psychology* **68** 372–385
- Gleitman H, 1995 *Psychology* 4th edition (New York: Norton)
- Goldstein E B, 1999 *Sensation and Perception* 5th edition (Pacific Grove, CA: Brooks/Cole)
- Gombrich E, 1972 *Art and Illusion* 2nd edition (Princeton, NJ: Princeton University Press)
- Gombrich E, 1982 *The Image and the Eye* (Ithaca, NY: Cornell University Press)
- Goodman N, 1968 *The Languages of Art* (Indianapolis, IN: Bobbs-Merrill)
- Gordon I E, 1997 *Theories of Visual Perception* 2nd edition (Chichester, Sussex: John Wiley)
- Hagen M A, 1986 *Varieties of Realism* (New York: Cambridge University Press)
- Helmholtz H von, 1866/1925 *Treatise on Physiological Optics* volume 3 (English translation by J P C Southall (1925, Menasha, WI: Optical Society of America) from the 3rd German edition of *Handbuch der physiologischen Optik* (1910, Hamburg: Voss)
- Hershenson M, 1999 *Visual Space Perception* (Cambridge, MA: MIT Press)
- Hochberg J, 1978 *Perception* 2nd edition (Englewood Cliffs, NJ: Prentice Hall)
- Hochberg J, 1990 "After the revolution" *Contemporary Psychology* **35** 750–752
- Hoffman K P, 1986 "Visual inputs relevant for optokinetic nystagmus in mammals" *Progress in Brain Research* **64** 75–84
- Ikeuchi K, Horn B K P, 1981 "Numerical shape from shading and occluding boundaries" *Artificial Intelligence* **17** 141–184
- Ittelson W H, 1996 "Visual perception of markings" *Psychonomic Bulletin & Review* **3** 171–187
- Kelso J A S, 1995 *Dynamic Patterns* (Cambridge, MA: MIT Press)
- Kim N-G, Growney R, Turvey M T, 1996 "Optical flow not retinal flow is the basis of wayfinding on foot" *Journal of Experimental Psychology: Human Perception and Performance* **22** 1314–1319
- Land M, 1999 "Motion and vision: Why animals move their eyes" *Journal of Comparative Physiology A* **185** 341–352
- Land M F, Lee D N, 1994 "Where we look when we steer" *Nature (London)* **369** 742–744
- Lappe M, Bremmer F, van den Berg A V, 1999 "Perception of self-motion from visual flow" *Current Trends in Cognitive Science* **3** 329–336
- Lee D N, 1980 "The optic flow field" *Philosophical Transactions of the Royal Society, London B* **290** 169–179

- Levine M W, Shefner J M, 1981 *Fundamentals of Sensation and Perception* (Reading, MA: Addison-Wesley)
- Marr D, 1982 *Vision* (San Francisco, CA: Freeman)
- Matlin M W, Foley H J, 1992 *Sensation and Perception* 3rd edition (Boston, MA: Allyn and Bacon)
- Maunsell J R H, Newsome W T, 1987 "Visual processing in monkey striate cortex" *Annual Review of Neuroscience* **10** 363–401
- Mitchell W J T, 1986 *Iconology: Image, Text, Ideology* (Chicago, IL: University of Chicago Press)
- Nakayama K, 1995 "James J Gibson—an appreciation" *Psychological Review* **101** 324–328
- Neisser U, 1990 "Gibson's revolution" *Contemporary Psychology* **35** 749–750
- Palmer S E, 1999 *Vision Science: Photons to Phenomenology* (Cambridge, MA: MIT Press)
- Reed, E S, 1988 *James J Gibson and the Psychology of Perception* (New Haven, CT: Yale University Press)
- Reed E S, 1996 *Encountering the World* (New York: Oxford)
- Restle F, 1980 "The seer of Ithaca" *Contemporary Psychology* **25** 291–293
- Royden C S, Banks M S, Crowell J A, 1992 "The perception of heading during eye movements" *Nature (London)* **360** 583–585
- Sabra A I (Ed. and transl.), 1989 *The Optics of Ibn Al-Haytham. Books I–III on Direct Vision* (London: The Warburg Institute)
- Schier F, 1986 *Deeper into Pictures* (Cambridge, UK: Cambridge University Press)
- Schiff W, 1980 *Perception: An Applied Approach* (Boston, MA: Houghton Mifflin)
- Sekuler R, Blake R, 1994 *Perception* 3rd edition (New York: McGraw-Hill)
- Smith N K (Transl.), 1958 *Descartes: Philosophical Writings* (New York: Modern Library)
- Snyder J P, 1993 *Flattening the Earth: 2000 Years of Map Projections* (Chicago, IL: University of Chicago Press)
- Steers J A, 1927 *An Introduction to the Study of Map Projection* (London: University of London Press)
- Stone L S, Perrone J, 1997 "Human heading estimation during visually simulated curvilinear motion" *Vision Research* **37** 573–590
- Turvey M T, 1990 "Coordination" *American Psychologist* **45** 938–953
- Turvey M T, Carello C, 1986 "The ecological approach to perceiving-acting: A pictorial essay" *Acta Psychologica* **63** 133–155
- Van Essen D C, 1985 "Functional organization of primate visual cortex", in *Cerebral Cortex* volume 3, Eds A Peters, E G Jones (New York: Plenum) pp 259–329
- Vishton P M, Cutting J E, 1995 "Wayfinding, displacements, and mental maps: Velocity fields are not typically used to determine one's aimpoint" *Journal of Experimental Psychology: Human Perception and Performance* **21** 978–995
- Wagner M, Baird J C, Barbaresi W, 1981 "The locus of environmental attention" *Journal of Environmental Psychology* **1** 195–201
- Wang R F, Cutting J E, 1999 "Where we go with a little good information" *Psychological Science* **10** 71–75
- Warren R, Wertheim A H (Eds), 1990 *Perception and Control of Self-motion* (Hillsdale, NJ: Lawrence Erlbaum Associates)
- Warren W H, 1995 "Self-motion: Visual perception and visual control", in *Perception of Space and Motion* Eds W Epstein, S Rogers (San Diego, CA: Academic Press) pp 263–325
- Warren W H, 1998a "The state of flow", in *High-level Motion Processing* Ed. T Watanabe (Cambridge, MA: MIT Press) pp 315–358
- Warren W H, 1998b "Visually controlled locomotion: 40 years later" *Ecological Psychology* **10** 177–219
- Warren W H, Morris M W, Kalish M, 1988 "Perception of translational heading from optical flow" *Journal of Experimental Psychology: Human Perception and Performance* **14** 644–660