Perception, 2002, volume 31, pages 1165 – 1193

DOI:10.1068/p3318

Representing motion in a static image: constraints and parallels in art, science, and popular culture

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Received 10 January 2002, in revised form 30 May 2002; published online 3 September 2002

Abstract. Representing motion in a picture is a challenge to artists, scientists, and all other imagemakers. Moreover, it presents a problem that will not go away with electronic and digital media, because often the pedagogical purpose of the representation of motion is more important than the motion itself. All satisfactory solutions evoke motion—for example, dynamic balance (or broken symmetry), stroboscopic sequences, affine shear (or forward lean), and photographic blur—but they also typically sacrifice the accuracy of the motion represented, a solution often unsuitable for science. Vector representations superimposed on static images allow for accuracy, but are not applicable to all situations. Workable solutions are almost certainly case specific and subject to continual evolution through exploration by imagemakers.

1 Introduction

> "While the problem of space and its representation in art has occupied the attention of art historians to an almost exaggerated degree, the corresponding problem of time and the representation of movement has been strangely neglected."
>
> Gombrich (1982, page 40)

Authors in many disciplines illustrate their texts. When they write about—or simply want to include a pictorial description of—the motion of air, waves, objects, continents, galaxies, or most importantly people, this could become a particular problem. Words often do little justice to motion, and it might appear that static images could do little better. How can one depict motion in a medium where none can exist? Successfully meeting this challenge is not straightforward in any arena, be it art, science, or popular culture. Artists and scientists, often independently, have stumbled across various solutions.[1] Nonetheless, there has been no full catalog of various styles, few assessments of successes and failures, and no attempt to provide guidelines for imagemakers about what works, when, and why.

Indeed, following from his statement above, Gombrich (1982) proposed that "no systematic treatment has ever been attempted" (page 40). This is no longer quite true. Friedman and Stevenson (1975, 1980) distinguished between more natural, postural representations of motion, which seemed easy to understand, and metaphorical indicators of movements, like arrows or action lines, which may be less so. However, Carello et al (1986) found little psychological support for this distinction. In addition, Braddick (1995)

[1] There are many kinds of motion illusions in still images. For example, imagine a lattice of small black squares, each row offset such that every other row is aligned creating 45° diagonals. Gazing at any particular locale can often yield the perception of a shooting motion up and down the diagonals. This effect is called Springer's lines (see, for example, Laming 1992). In addition, many moiré patterns yield a kind of motion. The best configurations generating these are high contrast black and white curved lines, as in much of the op art by Bridget Riley (see De Sausmarez 1970). Gottlieb (1978) called these *flicker*. In addition, there is the Ouchi illusion (Ouchi 1977; Fermüller et al 2000) of motion in stationary, staggered plaids; and the McKay, or Venetian blind, illusion of high-contrast radial stripes and chromatic rings (Livingstone 2002).

also discussed a few techniques for representing motion, but focused mostly on motion itself. Here, I discuss only representations of motion—and without data—for the purpose of exploring a typology of depicted motions. What is compelling, however, is that the few techniques used are found almost equally in art and in science. Concretely, my purpose is to illustrate and discuss five different types of representations of motion, each of which is reasonably separable and distinct. They may not be exhaustive, but they do cover most of the territory. But first, returning to Gombrich, one needs to understand why the categorization of the representations of motion has been neglected. Any explanation for neglect may turn on a particular pair of ideas.

2 Moment and instant

Consider the *instant*. In its contemporary form, the basis of this idea almost certainly stems, as do so many aspects of modern culture, from the radical changes in modern life that occurred in the 19th century. Important milestones included the development of the railroads and timetables to run them; of the standardization of time in Europe and America so that train schedules could be adhered to; and of relatively inexpensive but accurate watches so that individuals could keep tabs on, among other things, train arrivals and departures (Kern 1983; Schivelbusch 1986; Whitrow 1988). Perhaps for the first time in the history of humankind almost anyone could make or miss a planned event in an instant—in this case the departure of a train. Moreover, since the populace of several Western nations could take trains for journeys, even mass transit, there was widespread understanding of such instants. With respect to the concerns of this paper, however, the instant is better exemplified by the development of fast-film photography and its once shocking results. Instantaneous images of the running horse and the walking man captured the imagination of—and infuriated—intellectuals, artists, and the bourgeois in Western Europe and North America.

Artistic, scientific, and cultural responses to the photographic work of Muybridge (1887) and Marey (1894)—particularly with their representations of gallops and gait—were numerous and disparate (Scharf 1974). Before their work, few had ever thought about motion captured in an instant; after it no one would ever mistake the fact that instants were quicker than the human senses could register.[(2)] Public debate raged whether truth was in the instantaneous photographic image of an event, or in the human eye's reception of the event. Perhaps for the first time one was faced with a situation in which he or she had to choose between obvious physical truths and compelling psychological truths.

With the passage of time and the imperative of technology, physical truth would win out, forging a new psychological truth. Subsequent developments in stroboscopic photography, and in modern engineering and physics more generally, led to instants that were smaller and smaller slices of time. Harold Edgerton—even before the advent of Superman—could capture the course of a speeding bullet (see Bruce 1994; Edgerton and Killian 1979). Month after month in the *Technology Review* of the early 1930s, Edgerton astonished a broad public with his photographs of bullets shattering light bulbs and playing cards, and of droplets of milk rebounding into coronets and circular waves. Shortly thereafter, physicists could capture the path of an electron in a bubble chamber moving at untold velocities (eg Robin 1992). With all of this, two new facts emerged. First, all further subdivisions of instants shared the characteristic of being more fleeting than the eye could register. Thus, in an important sense all such instants

[(2)] Exceptions are a small group of scientists interested in various aspects of physics and perception who used sparks to present brief flashes and observe what could be seen. These include Helmholtz, Exner, Mach, and others, all slightly prior to the public interest in Muybridge and Marey. See Wade (1998, pages 192–210) for an historical overview. However, the point being made concerns images as read by large segments of a culture's population.

are the same. Second, the rapidly acculturating human eye would never again expect the same things from any image.

Before the advent of the photographic instant there was the artistic *moment*. This slice of time is something broader and rounder, encapsulating an entire event. The moment is eminently captured in artworks of almost any period before the mid-19th century. Such images coalesce the décalage of important aspects of a scene into one set of gestures, postures, and arrangements of people and objects that tell a story, or at least part of it. Gombrich (1982, page 44) provided a modern example concerning what is represented in a moment versus an instant:

> "The so-called 'stills' which we see displayed outside cinemas and in books on the art of the film are not, as a rule, simple isolated frames from the moving picture enlarged and mounted. They are specially made and very often specially posed on the set, after the scene is taken. That thrilling scene where the hero embraces his girl while he keeps the villain covered with a revolver may consist of many yards of film containing twenty-four frames per second of running time, but not one of them may be really suitable for enlargement and display."

The dramatic *moment* is portrayed in this promotional advertisement; an *instant* by an individual frame of the movie. The advertising image shows many of the important aspects of the narrative sequence—forced together at the same apparent time and in the same space—even though they did not, in a discrete physical sense, occur that way in the instants captured on film. The moment could capture the psychological truth of the event—something that no instant could do.

Images in art, at least prior to the mid-19th century, generally work this same way. They are not like photographs and they were not meant to be read like photographs, despite our default tendency to do so today. Most such images are fashioned so that the composition reflects an event as it would have unfolded over some, often extended, period of time. Often multiple, related images—triptychs, chapel walls and ceilings, scroll and cloud paintings, tapestries, and the like—tell a longer story with many episodes, each of which is captured in separately portrayed moments. In this manner the representation of motion only becomes a problem if one thinks of any picture as a frozen instant in time. In most pre-20th-century artwork this simply isn't true; a story is being told.(3) The iconography behind what is apparent in the picture tells the story; that iconography is known collectively by those who would see the picture at the time of its composition, and that story often carries implicit motion in the scene.

Thus, while historical discussion of art before the 20th century is replete with accounts of the depiction of space, it need not be full of discussions of time. Time is in the narrative, and instants did not exist. Of course, some modern and contemporary art explicitly explores the instant and the problems of capturing it as, for example, shown in figure 1 by the delightful image, *Action Painting* (1981), by Mark Tansey. Provocatively, it contains a painting within a painting. The artist working at the canvas is carefully measuring the moment of her subject, working over a period of time. The instant of the car screeching out of control, of course, cannot be captured in the moments of a careful artist, at least not in real time and on the scene. And yet Tansey, whose mother was an artist and father an art historian, shows us that at least his depicted artist has succeeded in freezing the instant of physical time, allowing her to compose across the moment of painting it. Tansey often explored this theme (see Danto 1992).

Of course, most of the history of art is not concerned with the instant, only with the moment, even sequence of moments. Thus, as Gombrich (1982) knew well, the

(3) As noted by Alpers (1983), this view is most true for a southern European tradition. Images from the northern Renaissance tell less a story than describe the environment that is seen. Nonetheless, in such images it is still the moment that is described, not an instant within the moment.

Figure 1. *Action Painting* (1981) by Mark Tansey. In this image Tansey shows the artistic moment (on the artist's easel) capturing an instant within a car crash (reprinted with permission of Mr Tansey and the Gagosian Gallery, NY).

representation of motion is in fact not a topic like the representation of space, and it could not occupy the same kind of niche in the history of art, or for that matter psychology. But such representations are also seldom part of the study of science either. At best they are a sidelight, and even then the concerns are usually with graphs and charts, not with images and motion.[4] Thus, there are practical, if not completely justifiable, reasons for the dearth of analyses of the representations of motion in art and science. They fall outside the typical domain of any discipline. Even those interested in the burgeoning field of scientific visualization (eg Friedhoff and Benson 1991; Tufte 1983, 1990) show little interest in motion. Part of my purpose is to promote a need to understand these images.

Why? What is there to be understood? After the appearance of the photographic instant, and over the course of more than a century of exposure to it, it is likely that viewers of images increasingly expect that instants would be portrayed in all pictures. Following Baxandall (1972), our contemporary-period eyes are simply accustomed to, and biased toward, expecting snapshot-like qualities from all images. With this culturally and technologically driven imperative, the necessities of representing motion then tugged on all imagemakers in earnest. To what, then, did they turn? In my assessment, five roughly independent ideas took hold, all of which were extant in the late 19th and early 20th centuries and continue with us today.

[4] Many kinds of images appear in scientific texts. Excluded from this analysis is the understanding of standard photographs, which has received much attention (see Pirenne 1970; Deregowski 1989). Also excluded is the understanding of tables and graphs (see Bertin 1967; Cleveland 1985; Cleveland and McGill 1986; Kosslyn 1989; Spence 1990; Tufte 1983, 1990; Wainer 1997). Bertin (1967) is perhaps the most striking and comprehensive, suggesting that shape, orientation, texture, color, luminance (value in his terms) and size are the primitive graphical elements; thirty-five years later such a list sounds remarkably like a list of neurophysiological channels in vision (eg Spillmann and Werner 1990). Other examples include flow charts, box diagrams, maps, path diagrams, sociograms, and other spatial representations of theory, data, or methodology that attempt to show the logical layout of a domain as conceived by the scientist. Some of these have their own conventions—such as maps (see Monmonier 1991), multidimensional scaling solutions, and hierarchical clusterings (see Shepard 1980)—but others have no agreed-upon format and thus are more interesting. Most representations of motion are of this kind. For a cross-disciplinary approach to scientific images, see Lynch and Woolgar (1990).

3 Five ways to represent motion, and four criteria by which to judge them

Well before the inventions of photography, artists and their patrons felt the need to show human figures in a more-or-less natural pose. In portraying them, artists created figures in what is often called (a) dynamic balance, broken symmetry, even instability. Among other goals, this technique seeks to break up appearances that would otherwise appear too static. So successful has it been that this device is very much still with us. Nonetheless, in some pictorial domains it does not suffice. The modern imagemaker often needs to teach the reader some specifics about motion, not simply to promote viewer empathy. These additional methods are (b) multiple images, (c) affine shear, (d) blur, and (e) vector-like lines superimposed on an image.

Not surprisingly, each solution often creates its own problems, which will be discussed in turn. These problems have likely promoted the exploration of other means of representation. Their efficacy will be discussed in terms of four criteria, increasingly focused on the necessities of science. These are given in table 1. The first is *evocativeness*. That is, does the representation succeed in evoking in the viewer a feeling of motion or movement? There is no clear, objective method for predicting this property. Nonetheless, without it the representation, whether in art or in science, simply fails.[5] Once met, however, other issues arise. A second criterion concerns the *clarity* of the object represented. That is, can one identify the object whose motion is represented, or the objects that designate one's own movement? Without meeting this criterion any representation loses some of its potential punch. To be sure, some vagueness about identity is allowable, particularly in art, but in a scientific illustration unidentifiability may render the image useless. A third criterion concerns the *direction* of depicted motion. Can one tell, by the style of representation itself, whether the figure is moving right or left, up or down? Context and knowledge surely help. An out-of-focus picture of a car, in the context of a clear background, will surely indicate forward motion of the car—simply because cars most often move forwards; indeed, they are designed that way. However, not all representations of motion or movement can rely on such knowledge by the observer. Finally, given direction information, one can ask about *precision*. More simply, how much motion has occurred? This criterion is applied almost exclusively in scientific illustrations, and is often critical. Science strives to present truth, and should not misrepresent data. Since representations of motion are most often intended to be read as data, they should be precise and accurate. Nonetheless, solutions often have their own aesthetic, and artists have often borrowed back these representations.

Table 1. Selected criteria for judging the efficacy of representations of motion.

Distinct solutions	Evocativeness	Clarity of object	Direction of motion	Precision of motion
Dynamic balance	√	√	~√	×
Multiple stroboscopic images	√	√	×	√
Affine shear/forward lean	√	√	√	×
Photographic blur	√	×	×	×
Image and action lines	√	√	√	√

[5] One can, of course, simply ask observers how successful (evocative) the motion depicted in an image is, and Carello et al (1986) did just that. Their results, however, point out a problem: once one is in the 'set' of judging motion, one may be doing something different than what one does spontaneously. Also, not all representations of motion are intended in evoke the impression of motion. Various dance notation systems, for example, are aimed at the reproducibility of human motion, not at capturing its impression (see, Dell 1970; Hutchinson 1970; von Laban 1966).

4 Motion in dynamic balance, broken symmetry, and notes on perceptual fluency and liberation by the new

> "One of the most elementary statements that can be made about any work of art is that it represents a dynamic pattern. Sometimes the whole work is organized around one dominant center, from which movement radiates throughout the entire area."
> Arnheim (1972, page 78)

This first representational scheme is a bit of a catchall, and for good reason. For centuries artists have struggled with the problem of making human and animal figures look more-or-less real and natural, or at least naturally posed. As suggested earlier (Friedman and Stevenson 1980; see also Ward 1979), postural representations of motion seem quite easy to read in images and quite natural to apply. Indeed, the technique of *contrapposto*—the positioning of the human figure in painting or sculpture with hips and legs turned in a direction different than the shoulders and arms—has been used since the Greeks (see Summers 1972). Since the Renaissance, the drape of long garments in portraiture also implies motion, or at least where the sitter had been. Mantegna, Leonardo, Raphael, and Titian, among many others, knew this technique well. Such devices were used, in part, because of the bilateral (also reflective, or mirror) symmetry of the human body. When seen from the front (or back) it can look static, immobile, and quite uninteresting. Equally, other objects and even the scenes themselves should not be composed too symmetrically.

Perfect bilateral symmetry can have a perceptually stultifying effect.(6) Consider Attneave (1955), who had people memorize the locations of dots in briefly presented patterns. He found that people made fewer errors on the bilaterally symmetric patterns than on random patterns. Thus, the symmetric patterns can be apprehended more rapidly, a phenomenon more recently called *perceptual fluency* (eg Jacoby and Dallas 1981; Crabb and Dark 1999). Going beyond Attneave, this fluency may also be correlated with boringness, and Gombrich (1984, pages 8–9) would appear to have agreed. In describing a path of completely regular flagstones, which can demonstrate other kinds of symmetries as well as reflective, he described the pleasant effects of breakages in the pattern:

> "This is the insight which the ancients summed up in the proverb '*variatio delectat*', variety delights. We look at the grid and take it in at a glance as soon as we have grasped the underlying rule that all the flagstones are identical. But the very ease of perception also accounts for the boredom that is caused by such monotony."

Broken symmetries may cause viewers to move their eyes more readily across a pattern and, when discrepancies to symmetry are found, interest often follows.

Thus in art, as in science (Weyl 1952), theorists have recommended that symmetry be broken, or played with. In practice this often means the overall patterns may approximate generally symmetry but that details within the patterns do not. Consider a naturally occurring analog: part of the appeal of snowflakes (see Bentley and Humphreys 1962) is that they have a six-fold rotational symmetry created during their formation that is broken by buffeting and partial melting during their fall to earth. Broken symmetry introduces perceptual effects, often called dynamic balance, even imbalance (see Arnheim 1974, 1982; Gombrich 1982; Gottlieb 1988; Groenewegen-Frankfort 1951). Among other things, these appear to breathe interest, even life, into a figure.

(6) An exception to the boringness of symmetry concerns faces and their perception. There can be great beauty in the symmetrical face over asymmetrical ones (see, for example, Rhodes 1996), although attractiveness demands other facial attributes (Rhodes et al 1999).

Exploring the underpinnings of contrapposto, Albrecht Dürer demonstrated for students that, when drawing the human figure, the lines connecting the two hips and the two shoulders should be canted, typically lifting one hip and dipping the shoulder on the same side. Of course, hair and clothing can blow in the wind, adding a certain amount of dynamism to a person as an artistic object, but it is the posture of that individual that is most important. Two examples are shown in the top panels of figure 2. The opposed slants of the hips and shoulders in each figure break the symmetry in a manner that is also quite natural to human movement. The breakages occur around a point near the navel, slightly lower for the male figure than the female. Cutting et al (1978), in some sympathy with Arnheim (1974, 1982), called this point the *center of moment*. By varying its location in a computer-generated human-like structure undergoing the normal pendular motions of bipedal gait, one can generate natural-looking, and discernibly different, male and female gaits (Cutting 1978).

There is, however, much more to symmetry than just reflection across a midline, just as there is much more to the aesthetics than breaking the symmetry of pose in the human body. Breakages of symmetry are at work in the design of small patterns in decorative art (Gombrich 1984) and in the largest cathedrals. Even for those built in the 20th century, cathedrals typically have naves that are not quite straight.(7) This occurs despite the fact that the architect and builders in any era were perfectly capable of constructing a cathedral with a straight nave. But entering and looking straight down the nave to the choir and cross must have been judged as too static, too symmetric, or—worse—perhaps an attempt to challenge the perfection of God.

Other graphically relevant symmetries include translation, rotation, and glide reflection (see Grünbaum and Shephard 1987). Translational symmetries are familiar in the tilings of many graphic works in Escher (Bool et al 1981), rotational symmetries in various cultural objects such as rose windows and yins and yangs, and glide reflections in paired footprints of a person walking on the sand. But notice that most of these are typically not completely symmetrical; they only approximate it, even play with it. These types of symmetry are particularly relevant to the decorative arts—wallpaper, friezes, decorative borders of all kinds (Gombrich 1984)—and they have also received some perceptual, scientific investigation (see, for example, Kubovy and Wagemans 1995).

There also seems to be an important relation between broken symmetry and dynamic balance on the one hand, and familiarity on the other. A particularly interesting example can be seen in the lower panels of figure 2 for Myron's copy of *Discobolos*, the discus thrower.(8) The lower left panel shows the standard view. It demonstrates an extreme contrapposto, a dynamic balance needed to evoke motion, and portrays a tension-like quality of a coiled spring. Unfortunately, such a figure is also so overwhelmingly familiar as to be a cliché. It is difficult to look through our familiarity with this pose to see what is actually happening. The adjacent panel, on the other hand, is a noncanonical view of the same sculpture, and most people would not have seen it before. Notice that it virtually seethes with motion, the figure leaning into the forthcoming discus throw. The difference cannot be due to symmetry. The evocativeness of the rear view may stem from the idea that the noncanonical liberates us from cliché. It allows us to see the potential of motion in the sculpture, which was clearly the intent of the artist, but which was lost in its familiarity from a particular viewpoint.

(7) I have been unable to find a literature on this, even after consulting colleagues in architecture. Nonetheless, visits to Notre Dame (Paris), Chartres, and Amiens in France; and St John the Divine (NY) and the National Cathedral (DC) in the US affirm nave curvature.

(8) The Myron *Discobolos* figure was also used by Gombrich (1982, page 60) in discussing motion. But Gombrich discussed these views in terms of their differential legibility; here I make a different point. See also Ward (1979, page 248).

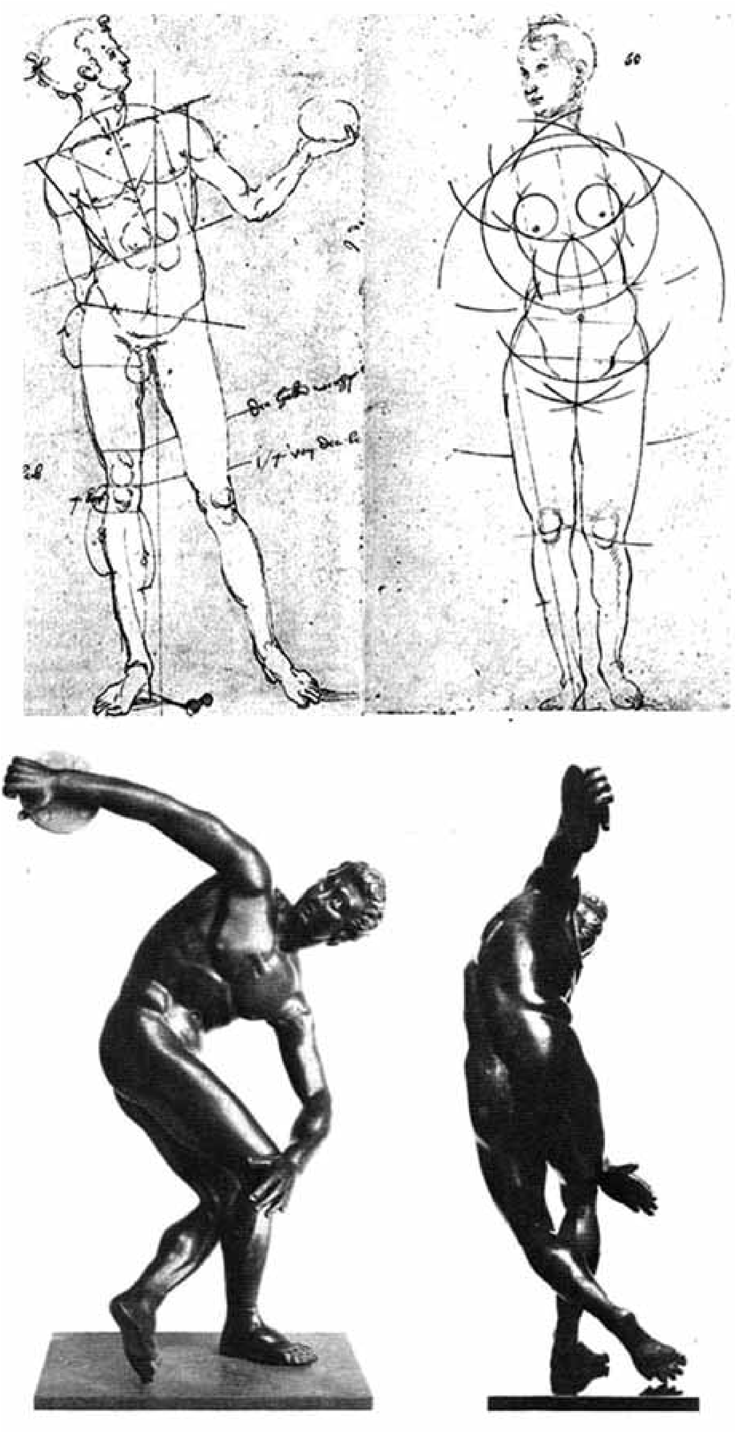

Figure 2. Examples of motion represented, or at least implied, in the dynamic balance or broken symmetry of the human form. The top panels are by Albrecht Dürer (Strauss 1972) (reprinted with permission of Dover Press). The bottom panels show two views of the small bronze statue of *Discobolos* (the discus thrower) by Myron (reprinted with the permission of the Staatliche Antikensammlungen, Munich). The left panel is the more familiar and the right the more evocative, perhaps because of its unfamiliarity.

Palmer et al (1981) studied canonical and noncanonical views of objects, and found that observers can name and categorize objects considerably faster in the former. As with complete symmetry, however, it may be that this reflexive speed is achieved at a cost. It may serve to inhibit a fuller intellectual and emotional appreciation. Again, perceptual fluency may diminish the opportunity for appreciation. This latter effect—the decreasing evocativeness of a dynamic image with its increasing familarity—presents a serious challenge to graphic artists. It warns them, and the rest of us, that, as a representation of motion becomes more familiar and is read more easily, it may also rob the image of motion of the very property it was designed to evoke. Indeed, this may be a driving force behind the discovery of new ways to represent motion. Other forces were certainly the new needs appreciated by imagemakers—that of representing a moving object clearly, that of representing the direction of motion, and that of representing it precisely. These needs would be met, more or less, by other techniques.

5 Motion as time discretely sampled: multiple stroboscopic images

"A running horse has not four legs, but twenty, and its movements are triangular."
Technical Manifesto on Futurist Painting
(Tisdall and Bozzolla 1977, page 33)

If one image does not work to represent the motion an imagemaker desires, perhaps two or more will do. Unlike a single image, a series of discrete static images can sometimes render the impression of motion without sacrificing the resolution, or visual clarity, of the moving object. There is a clear cost to the painter and printmaker in making separate, slightly different images, but that cost is vastly diminished for the photographer. Thus, early graphic solutions tended to use a single image; early photographic solutions many of them. Interestingly, however, the rudiments of a selective 'multiple-exposure' technique can be found at least two to three hundred years before the advent of photography. Consider the images shown in figure 3. All are particularly interesting achievements in the sharing of coordinates.

First, in the upper left panel is Leonardo's *Vitruvian Man*, today one of his most famous images. It is evocative. Motion—or at least the ability to move—can easily be interpreted from it. Here is a man with a torso and head but with four arms and four legs. The oneness of torso and head and multiplicity of limbs is striking. Surely cannot anyone at anytime see that the limbs can move around the body? Almost surely not. The image—in homage to Vitruvius [1st century BC] and his writings on architecture, form, and symmetry—represents the universality of man in harmony with the geometry of the world (eg Crowe 1995). It clearly was *not* intended to represent a fellow doing calisthenics, although students almost universally read it that way today.(9) While the early 21st century eye may be almost obligated to see motion in this image, the late 16th to early 17th century eye was surely not. Again, such is the possible force of the period eye (Baxandall 1972). But this only serves to reinforce an important point: Graphic artists have struggled with forms of representation for millennia. Some solutions to a problem of one period may be read as a solution to a different problem in a later period.

(9) Similarly, *pentimenti*—the multiple copies of figures in different positions, often revealed over time through the aging of superimposed layers of paints—can be read today as revealing motion, but were almost surely not intended as so.

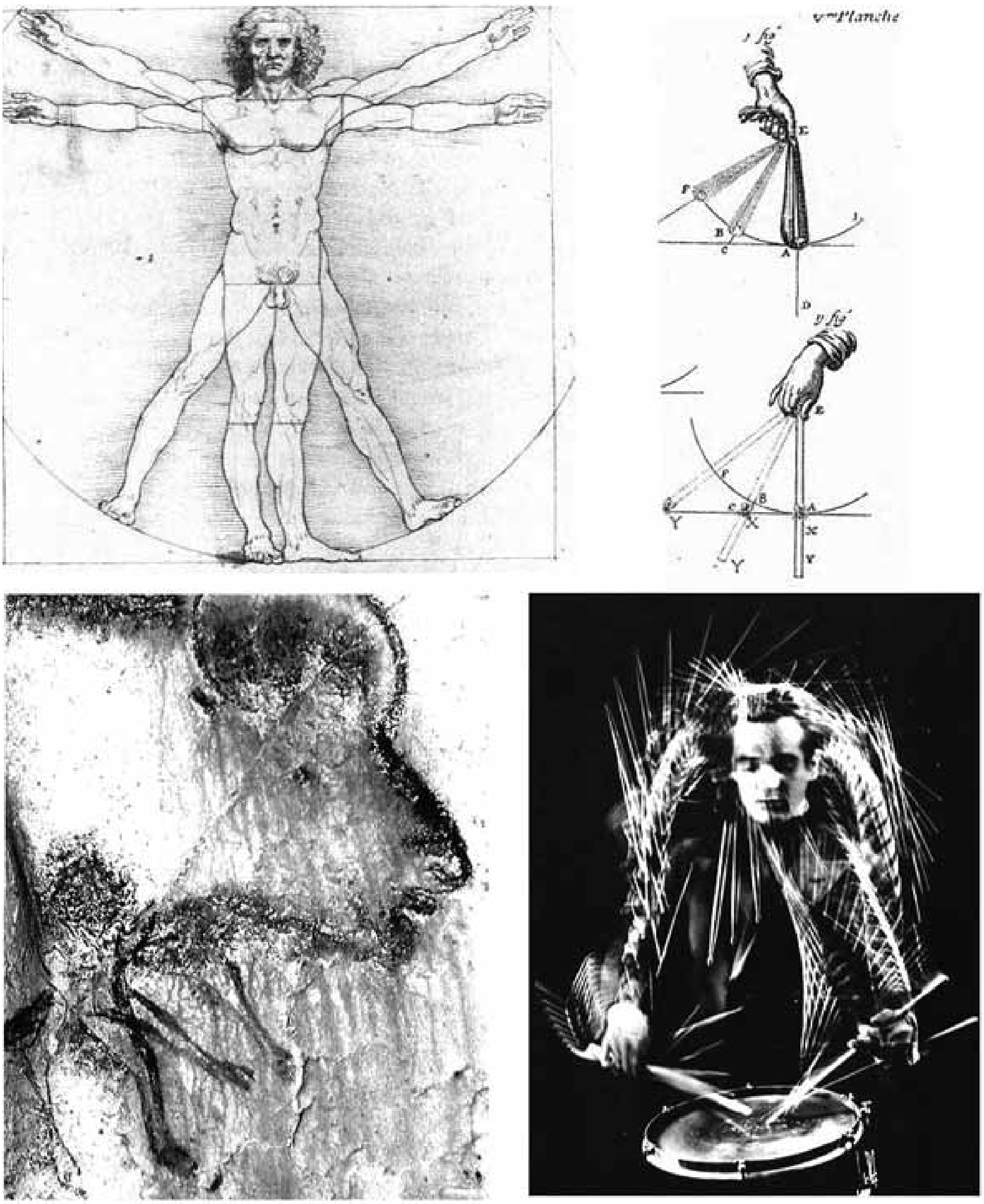

Figure 3. Possible early examples of stroboscopic representations of motion. The top left panel is the much discussed *Vitruvian Man* (~1494) by Leonardo da Vinci in the Accademia, Venice (reprinted with permission of the Ministero per i Beni e le Attivitá Culturali). It was almost certainly designed without the idea of motion. The top right panel is by Descartes, from his *Meditations* (eg Descartes 1680). It is unarguably about motion. The bottom left panel shows a possible example of depicted motion from paleolithic art, drawn perhaps 32 000 years BPE (Clottes 2001) (reprinted with permmission of Mr Clottes). The bottom right panel shows a stroboscopic image by Gjon Mili of Gene Krupa (~1941, reprinted with permission of Time Life Inc).

When did this mode for representing motion originate? If not with Leonardo, then with whom? Consider next some illustrations from Descartes' *Meditations* (eg Descartes 1680) shown in the upper right panel of figure 3. These were drawn only a few decades after *Vitruvian Man*. Their purpose was to display the pendular motions of a sling and stick, to which Descartes felt that his text could not do justice. Each is shown in three positions and held in an unmoving hand. Notice, particularly with respect to the sling, that the condensation of coordinates is critical. That is, the hand is held fixed in position in the image, even though it would not be in the real world either when slinging a rock or when dangling the device like a pendulum. Stroboscopic photography of a dangling sling would emphatically not show such images without extreme care in composition. Thus, following on from the introductory discussion, Descartes' image—which he may have drawn, or at least designed, himself[10]—represents the moment of slinging, more than its separate instants.

Although motion is misread in the *Vitruvian Man*, it seems there is no room for doubt of Descartes' intent: His image shows the potential of motion in a static image. It is tempting to think that Descartes may have been aware of Leonardo's image, but this is unlikely since it was first published by Carlo Guiseppe Gerli a decade after Descartes' death (Turner 1993). Nonetheless, this lack of contact between the two can reinforce several points: The constraints placed on the various psychologically acceptable representations of motion are many, the number of aspects in an image that can be communicated (such as motion) is also constrained (Massironi 1989), and together the constraints and the search for new ways to communicate ideas are likely to force independent discovery.

Indeed, one can argue that a representation of motion, or at least the capacity to move, appears in some of the oldest paleolithic art. In the lower left panel of figure 3 is a bison with two right front legs. Either the artist changed his or her mind—as is often claimed when interpreting paleolithic art, and is undoubtedly true in many cases—or the artist wished to depict the bison in motion. The former seems unlikely since the raised leg is not a position of repose for such a beast. The unknown artist of this image may have scooped Descartes by 32 000 years (see also Chauvet et al 1995; Clottes 2001). Wachtel (1993) broached other cinematic aspects of paleolithic art.

Regardless of these antecedents, the multiple-image approach to representing motion burgeoned only in the late 19th century with fast film, fast lighting, and the photographic work of Muybridge and Marey. Muybridge, famous for his series on animals and human beings in motion, presented his subjects in a series of separate photographs. These relied on translational symmetry of an identical background (patterns of gridwork) seen across the separate images. Motion was clearly invoked, but was it sufficiently evoked? Marey's technique was technically simpler, more in line with its graphic predecessors—of which he undoubtedly knew since he also wrote on graphic representation (Marey 1878). It was also perceptually much more successful, at least as suggested by the plethora of imitators. Using a single set of environmental coordinates generated by the still camera, Marey typically superimposed images in a single photograph, much like those of Leonardo and Descartes, creating a technique that has been used most effectively elsewhere in art and in science to depict motion.

Consider an example from Marey, shown in the top panel of figure 4. The subject was a runner dressed in a black body stocking, lined with white stripes. To compose this image Marey had the camera and lens held stationary, but he illuminated the otherwise dark scene with stroboscopic flashes every 100 ms or so as the individual ran from left to right. The result is extremely effective because it allows one to see a clearly resolved (if schematic) person in multiple poses. Even better, for scientific purposes it invites comparison of structure across instants, and this is what Marey most wanted. Notice that one can see that different parts of the human body move faster than others during gait, and at different times.

[10] Gary Hatfield, personal communication, November 1999.

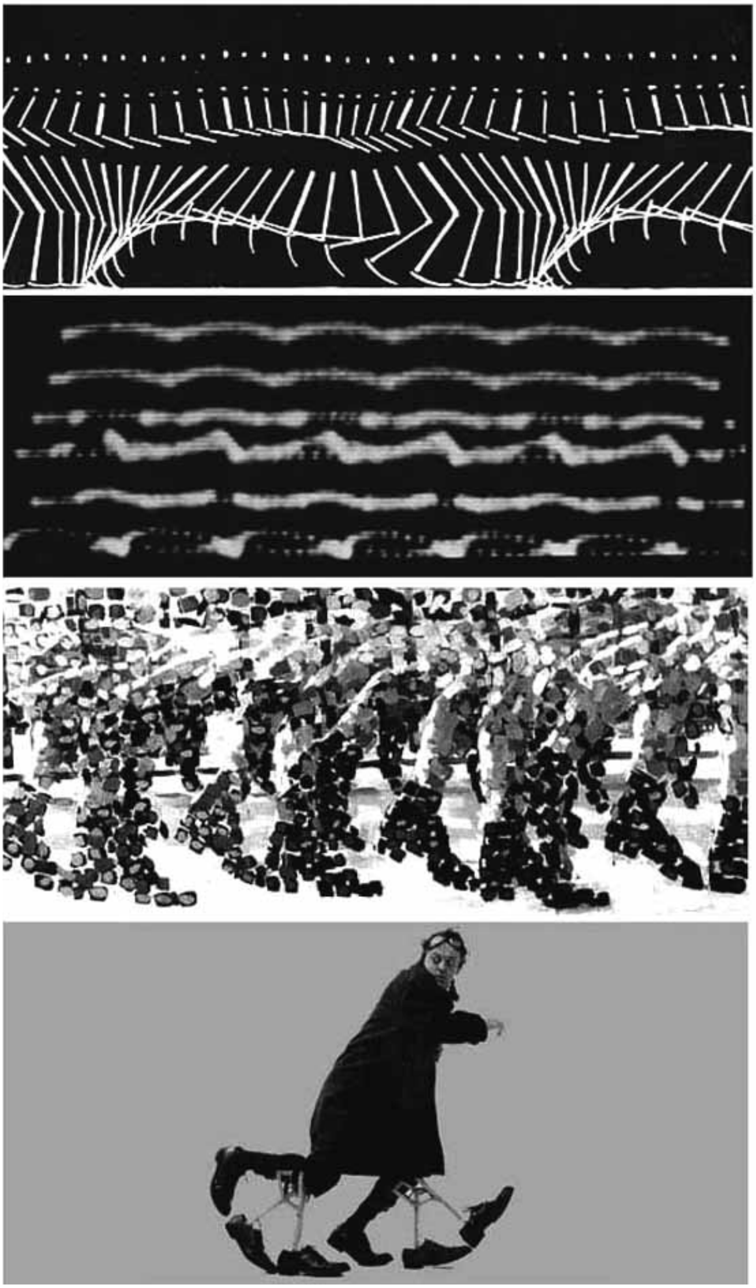

Figure 4. Four panels of pedestrians and representations of their movement. The top panel (*Course de l'Homme en Noir, Chronophotographie Géométrique Partielle* 1883; reprinted with permission of the Musée Marey, Beaune, France) is from a stroboscopic study by Marey (1894) of an individual running, left to right in a black body stocking. White tape was mounted along the arms, legs, and feet, and on the shoulder and head, while the scene was stroboscopically photographed. The second panel is a time-lapsed representation of an individual walking, left to right, over the course of about 3 s (6 steps). Lights were mounted as if on the major joints and on the head. This display was computer generated by the algorithm presented in Cutting (1978). The third panel is a detail from Giacomo Balla's *A Girl Running on the Balcony* (1912; reprinted with permission of the Civica Galleria d'Arte Moderna, Milan). The fourth panel, humorously elaborating Marey and Balla, is a photograph by D A Hill of the Canadian clown Tomáš Kubínek (reprinted with permission of Mr Kubínek).

The work of Marey and Muybridge excited both scientists and artists at the beginning of the 20th century. For example, the Russian physiologist Nikolai Bernstein (1934/1966) used the technique to study human locomotion. The impact of Bernstein's work has been widespread, and includes medical interest in hip replacement (Murray 1967), and in modern sports training. Muybridge also profoundly influenced the 20th century American engineer and photographer, Harold Edgerton, discussed earlier. Edgerton's student, Gjon Mili used Marey's technique for the performing arts. The example shown in the lower right panel of figure 3 is a compelling image of the virtuosity of mid-20th-century drummer, Gene Krupa.

Earlier in Europe, however, there was a delayed burst of nearly simultaneous activity in modern art influenced by Marey. The earliest may have been the Czech painter living in Paris, Frantisek Kupka. His *Woman Picking Flowers* (1910 – 1911) is shown in the top left panel of figure 5. It presents six or seven superimposed images of a woman rising from a chair, walking a few steps, and bending over. With her movement, these change colour from green to blue to red to orange. Somewhat later and also in Paris, Marcel Duchamp created several images which have the quality of multiple stroboscopic exposure. Perhaps his most famous are two called *Nude Descending a Staircase* (1912), both in the Philadelphia Museum of Art. One is shown at the top right of figure 5. Here the superposition of three cubist figures on a set of stairs, both with more than the normal compliment of arms and legs, evokes the perception of descent. And Luigi Russolo, an Italian Futurist, produced his *Plastic Synthesis of the Movements of a Woman* (1912), a superimposition of six or seven blue images of a woman walking and turning. All of these show homage to Marey. Well before them in 1877, and shown in the bottom right panel of figure 5, Marey sculpted (or had sculpted) a stroboscopic representation of a gull in flight. It has 34 wings, 17 concatenated bodies, and one head.

Kupka, Duchamp, and Russolo only dabbled with this technique. One of Russolo's colleagues, however, the Futurist painter Giacoma Balla was much more consistently interested in stroboscopic-like effects (see also Braddick 1995; Roche-Pézard 1979; Rowell 1975). The impact of Marey on Balla is unmistakable in a detail of his *A Girl Running on a Balcony* (1912), shown in the third panel of figure 4. Beyond the mosaic-like daubs of paint, Balla's image is composed as if it were produced by a stationary camera, capturing separate instants of action as the girl traverses the space portrayed. Balla successfully presented coherent images in the light from that flow. The playfulness of such images is also apparent, and is used to good advantage by the contemporary Canadian magician and clown 'Professor' Tomáš Kubínek, as shown in the bottom panel of figure 4. With his multiple foreleg device, Kubínek can walk quite rapidly and smoothly around a stage. He is also extremely funny.

Balla adapted and deftly elaborated stroboscopic techniques in other works. Consider his *Dog on a Leash* (1912), shown in top panel of figure 6. Here, the dog 'has not four legs', its mistress has well more than two, and the leash is also multiply represented, gracefully portraying harmonic motions. This image is different than Marey's, those of other artists, and even of Balla's other works. It is more like many in astronomy, as will be noted later. It is as if the camera (Balla's eye) moves to follow the dog and its mistress along the street, keeping them in mid-image while the background is blurred and streaked. It is like what would be seen when one's eye makes a pursuit fixation.

Multiple, stroboscopic displays are so effective at representing motion that even preschoolers seem to understand them (Friedman and Stevenson 1975). However, as a motion representation there remains a problem, suggested in table 1. Although the moving object is now clarified, one can still not overtly tell its direction of motion

Figure 5. Four other images from art representing stroboscopic images of motion. The top left is Frantisek Kupka's *Femme Cueillant des Fleurs* (1910 – 1911), Musée National d'Art Moderne, Paris [reprinted with permission of the Artists Rights Society, NY: © 2002 Artists Rights Society (ARS), New York/ADAGP, Paris]. The top right is Duchamp's *Nude Descending a Staircase No 2* [1912; reprinted with permission of the Artists Rights Society, © Artists Rights Society (ARS), New York; and the Philadelphia Museum of Art, The Louise and Walter Annenberg Collection]; and the bottom left is Luigi Russolo's *Synthèse Plastique des Mouvements d'une Femme* (1912), Musée de Grenoble (reprinted with the permission of Fondazione Russolo – Pratella). The bottom right panel shows a stroboscopic sculpture of Étienne-Jules Marey's *Vol de Mouette* (1887). The sculpture is part of the permanent collection of the Musée Marey, Beaune (France), although it has also been on display at the Musée d'Orsay, Paris (reprinted with permission of the Mairie de Beaune).

unless one is familiar with it. In Balla's *Dog on a Leash* and his *A Girl Running on a Balcony* the direction of movement is revealed only because we are familiar with the articulation of people and of dogs and we know that they walk forward; and in Marey's walker the same is true. This may seem of little importance, but if an artist or scientist wished to represent the motion of an unfamiliar object, this technique may confuse. Thus, an imagemaker might wish for a representation where a moving object can be seen crisply, and its direction of motion inherently revealed.

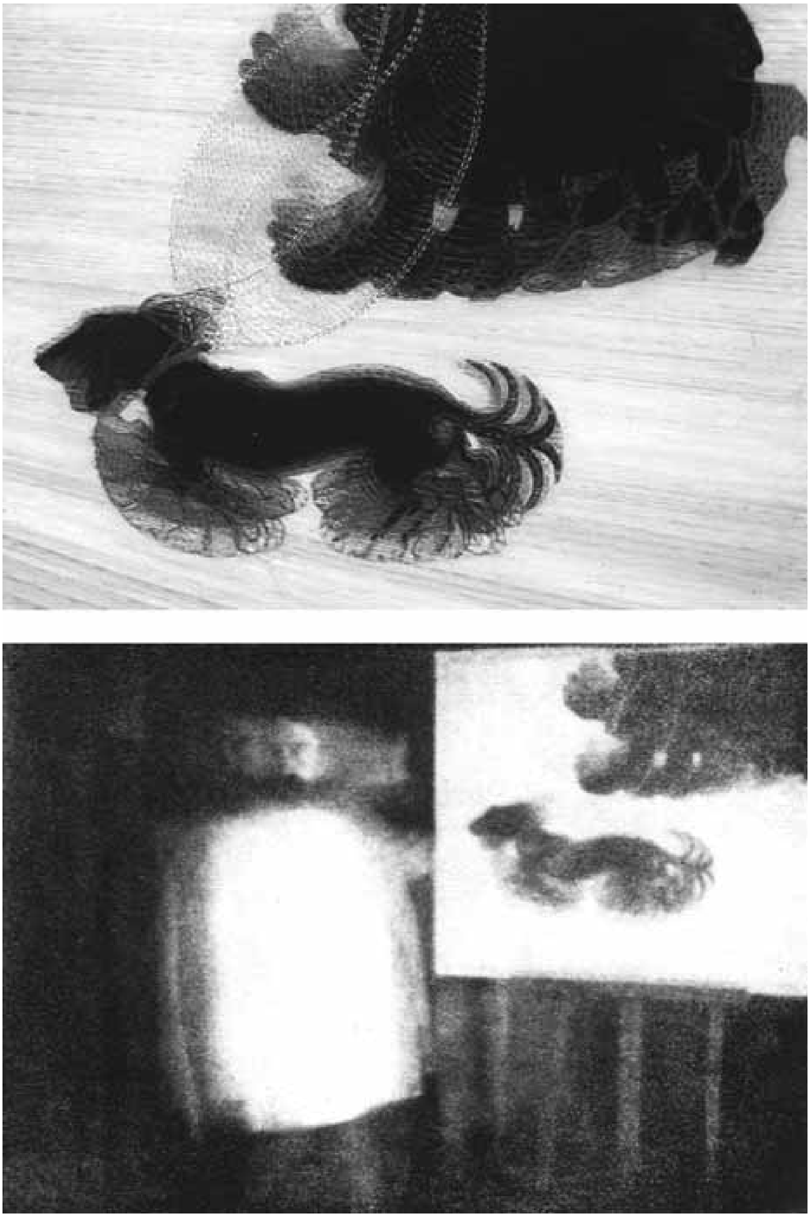

Figure 6. Two other representations of motion, one as multiple, superimposed images and the other as blur. The top panel is Giacomo Balla's *Dynamism of a Dog on a Leash* (1912; Albright-Knox Gallery, Bequest of A Conger Goodyear and Gift of George F Goodyear, 1964; reprinted with permission of the Albright-Knox Gallery, Buffalo, NY); the bottom panel is Bragaglia's playful 1912 photograph of *Balla in front of 'Dog on a Leash'* (reprinted with permission of SIAE, the Società Italiana degli Autori e Editori).

6 Motion as plasticity, affine shear, forward lean

> "Walt always loved trains.... In the story, the engine came to a grade where it was having trouble making headway ... [it] reached out and grabbed the rails as a person might grab a rope to pull himself along."
>
> Thomas and Johnson (1981, pages 73 – 74)

A third technique used by artists to represent motion was common throughout the 20th century and still is today—particularly as seen in the posters, comic strips, and animated cartoons of popular culture. A moving object is often depicted as leaning into its direction of movement. The technique is even successful when that object is inanimate, such as a car or a train, as shown in figure 7.

Consider a possible antecedent. As mentioned earlier, the 19th century was a time when the general populace was first subjected to speed. People watched trains, rode them, loved them, and feared them. In 1829 in England, George Stephenson's new steam locomotive, the *Rocket*, would hurtle down the tracks at 24 mph, an astonishing velocity at the time. In various spoofs and reports, writers and imagemakers wished to portray some of this newly acquired speed. One example is shown in the top panel of figure 7 (see also Wosk 1992 for a fuller discussion). The figure, a fictitious Mr Golightly, rides a steam rocket. Most pertinent is the fact that his upper body leans far forward. To be sure, his hat is blown off, his scarf trails behind, and his legs stretch forward, but it is the lean of the torso and head that is critical for this discussion, and for the effect of represented speed. This lean is appropriated in the depiction of the motion of inanimate objects. It is as if this object takes on the properties of a human being (see also Thomas and Johnson 1981) and, to initiate or to carry on with locomotion, it must lean forward as if to demonstrate the extra effort in overcoming inertia or in leaning against the wind. With respect to the criteria listed in table 1, the clarity of the object remains good, and the direction of motion is indicated by the lean. Indeed, dramatic use of lean in the representation of human motion is suggested in the work of Toulouse-Lautrec (Johnson 1957).

An early inanimate example is shown in the second panel of figure 7. It is Jacques-Henri Lartigue's 1911 photograph of a racecar, and it is perhaps his most famous (see Lartigue 1978). The image is an arresting example of the use of lean to represent motion. It is also a technologically interesting photographic feat. It was accomplished by using a camera with a focal-plane shutter. In such cameras, the shutter lies against the film and back plane. The film is exposed sequentially through a narrow slit in the shutter as two curtains move laterally across the back plane, one revealing and one re-covering the film. Here, Lartigue turned the camera on its side. The bottom part of the picture was exposed first and the upper part later; hence the forward lean of the car (Baatz 1997). Notice, however, that the people are leaning backwards by about the same degree. This was accomplished by panning the camera horizontally, left to right as the car passed, but at a rate about half as fast as the car. Time, as ones move up the image, left the stationary objects behind, and hence they lean to the left. The result of both effects is an evocation of movement and is, insofar as I have observed, perhaps unique in the middle history of photography. This is affine shear, and the use of this technique is now common in graphic arts.

Consider the Disney image in the third panel of figure 7, from the 1949 animated film *Ichabod and Mr Toad.* As suggested in the quotation above, Thomas and Johnson (1981) attributed the forward lean and various other gestures of trains to their anthropomorphic character. That is, animated trains must have personalities and struggling through difficult times is what people do. With a great load, people (and trains) should

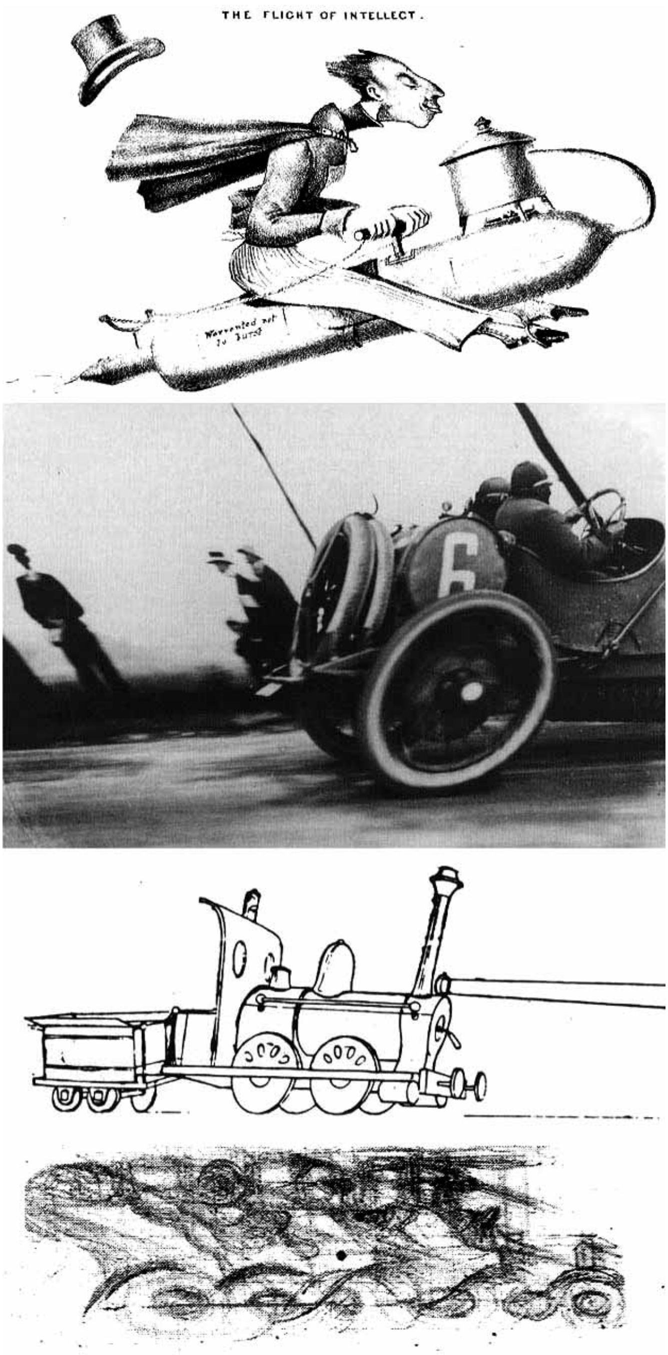

Figure 7. Four representations of motion using lean, three forward and one backward. The top image is a caricature and critique of early steam engines (reprinted with permission of the National Science Museum, UK). The second is Jacques-Henri Lartigue's photograph *Grand Prix of the Automobile Club of France* (1911; reprinted with permission of the Association des Amis de Jacques Henri Lartigue, © Ministère de la Culture—France/AAJHL). The third image is a reversal of a British design for the animated film short, *The Adventures of Ichabod and Mr Toad.* Reprinted from Thomas and Johnson (1981; © Disney Enterprises; reprinted with permission of Disney Publishing Worldwide). The bottom image is a reversal of a sketch by Giacomo Balla [© 2002 Artists Rights Society (ARS), New York/SIAE, Rome; reprinted with permission of the Artist's Rights Society].

lean forward to pull them. Apparently, Disney animation included such feats at least as early as *Mickey's Choo Choo* in 1929.

It is not clear when the convention of representing forward movement as a forward lean began, but it is clear that it was not fully in place in the second decade of the 20th century. As shown in the bottom panel of figure 7, Balla, an otherwise extremely acute observer of motion phenomena, depicted moving automobiles stroboscopically but as if leaning backward, wheels roaring ahead of the carriage.[11] Balla composed his image at about the same time that Lartigue photographed his. Despite the now-accepted convention, it is relatively rare that a forward lean is used alone to portray motion; it is often used with the fifth type of representational tool, which will be discussed later.

The success of this technique, like the others, creates new problems. These too are noted in table 1. First, a moment's reflection suggests that the amount of forward lean should be correlated with velocity or with acceleration. Even were this true over a series of images by the same artist, no absolute or even relative measure of speed can be made across all such images we might see. For example, in figure 7 is Lartigue's car going faster than Disney's train? Second and more important, the shape changes necessary to evoke speed—for example, changing a circular tire into an ellipsoidal one or the leaning forward of a train's smoke stack—are generally unsuitable for scientific illustration; these are affine distortions and suggest nonrigidity in objects that, in fact, are rigid.

7 Motion, evanescence, and photographic blur

> "The first photographs of urban scenes had an eerie, unnatural, sometimes surrealistic quality about them … . Only the most anonymous smears or ghostly vestiges faintly recorded some moving form or something that had suddenly moved off during the long exposure."
>
> Scharf (1974, page 169)

Perhaps the most obvious way to try to represent motion is through the use of blur in a relatively long-exposure photograph. In such a photograph, given a stationary framework and a moving object, one can begin to grasp motion in the still image. A classic example can be seen in figure 8, a 1936 image of the film star Lillian Gish taken by Edward Steichen for the magazine *Vanity Fair*. Notice that Gish's face is not blurred, but her arms, blouse, and even the tree behind seem to be moving, perhaps in sympathy with her swoon. Although this image may have been stunning in the first half of the 20th century, today it seems artificial, even stilted, perhaps in its use of blur.

Blurred photographs have two other problems as representations of motion, as suggested in table 1. First, as noted above and by its very nature, blur creates an unclear object. Carried to extreme it creates complete transparency, as can be seen in figure 9. These images from Lythgoe (1979) in a discussion of integration times in animal vision, contrast brief exposure with a long exposure—4 ms versus 4 s. Notice that, although the activity is the same in both images—a mother pushing her child on a swing—the child is quite crisply represented in the top image, but has disappeared in the bottom. This demonstrates that indistinctness of edges is only one of the effects of

[11] There is another interpretation. Consider the animated cartoon *Roadrunner* (Time Warner™). During what might be called active locomotion, characters lean forward, but during what might be called passive locomotion, they often lean backward. In particular, if the character's legs have the intention of moving, but his or her body has not yet achieved that intention, a backward lean is called for. This could easily be generalized to wheeled vehicles. However, it is not at all clear that Balla would have wished to express such an idea.

Figure 8. Edward Steichen's 1936 photograph of Lillian Gish, in the role of Ophelia, for *Vanity Fair* (reprinted with permission of Joanna T Steichen, and Steichen/Carousel). Note that the blur of Gish's and the tree's limbs, but the clarity of Gish's face.

blur; as suggested by Scharf (1974), above, transparency is another. Second, as with the previous modes of representation, blur fails to show the directionality of motion or of time, potentially confusing the viewer about the beginning versus the end of the action. Finally, consider the contrast in general effectiveness of blurred and stroboscopic representations. The lower panel of figure 6 shows a humorous image-within-an-image composed and photographed by Balla's colleague Anton Giulio Bragaglia, entitled *Balla in Front of 'Dog on a Leash'* (1912). Bragaglia used a long photographic exposure and portrayed the blurred motion of Balla turning away from (or turning towards) his painting. Balla's face is not fully distinct, but it does stand out from the blur of the turn. Bragaglia probably accomplished this by having Balla be still during a significant portion of the time that the lens was open exposing the film, and then having him turn. The juxtaposition of the blurred photography and the stroboscopically represented forms in the painting shows the general limitations of most blurred images and the clarity of stroboscopic ones.

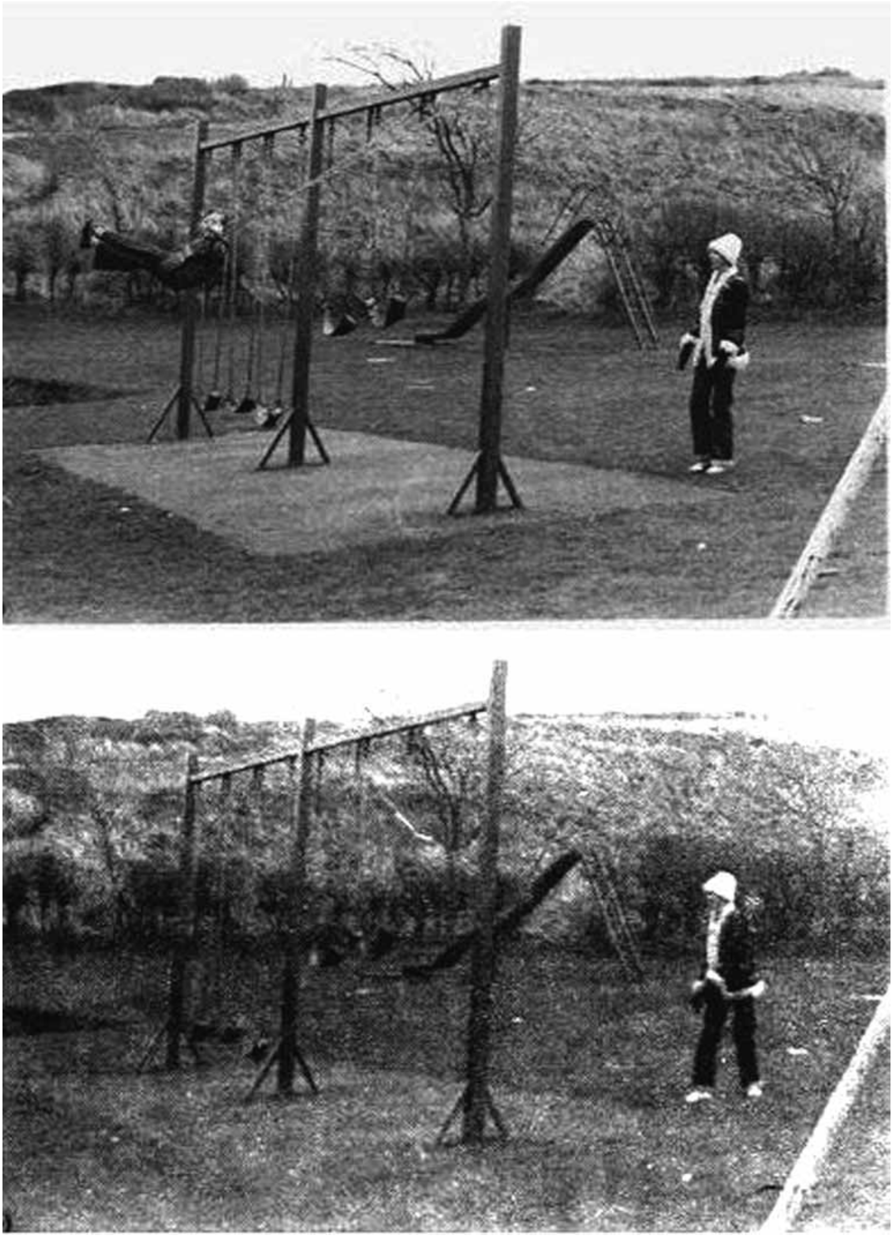

Figure 9. Two photographic images with different exposure durations. The top was taken with a 4 ms exposure; that at the bottom with a 4 s exposure, 1000 times longer. Note the disappearance of the child from the image in the latter [© Oxford University Press, 1979; reprinted from *The Ecology of Vision* by J N Lythgoe (1979) by permission of Oxford University Press].

8 Motion as action lines, zip-ribbons, and vectors

> "There is hardly a picture narrative in which speed is not conveniently rendered by a few strokes which act like negative arrows showing where the object has been a moment before."
>
> Gombrich (1972, page 229)

The final technique used by scientists and artists to represent motion in a still picture is, as Gombrich suggested, almost surely the most common in popular culture and in science. Moreover, it attempts to solve the previous problems of clarity and directionality, without succumbing to the problem of nonrigidity. The clarity of the moving object is obtained through the use of a single static image; the depiction of the direction of motion is obtained through an array of lines attached to the object; and thus the object need not be deformed. In the context of portraying motion, these are often called *action lines* (Brooks 1977; Carello et al 1986; Rosenblum et al 1993; Ward 1979), *speed lines* (Burr 2000; Kennedy 1982), or even *zip-ribbons* (McCloud 1993). Their antecedents, however, are in mathematics and are called *vectors*. Vectors developed out of Greek parallelograms as representations of forces and motion, but more particularly out of the mathematics of the early 19th century. Vectors are lines that have two properties—direction and extent. When used to represent motion, these two properties are the direction of motion and its speed—longer vectors mean faster motion, vectors pointing up mean upward motion, etc.

Vectors are typically drawn as arrows, but as long as the tails (representing the first instant of motion) and the heads (representing the most recent) are distinguished simple lines will do. Vectors, or action lines, are also seen in the work of Balla, as in figure 6. However, they are perhaps most commonly seen in cartoons, and they have existed in that medium at least since the strips and caricatures of Töpffer in the 1840s (Groensteen and Peeters 1994). Indeed, Friedman and Stevenson (1980) showed an example of action lines in an 11th or 12th century Japanese depiction.[12] Gilbreth and Gilbreth (1917) used action lines for the scientific study of efficiency in movement. Moreover, there appears to be some neurophysiological basis for their efficacy, for a quick flash of them can aid in the perception of motion in a static image (Burr 2000; Shepard and Zare 1983).

This fifth kind of representation has been used to advantage in several artistic and scientific domains. First, several photographic artists have used this technique to striking effect. Eric Staller, in a manner similar to the Gilbreths, opened up a camera lens for several minutes and passed through a night-time setting with a sparkler (the small celebratory, pyrotechnic device used by children and others). With these he created many patterns of streaks and diffuse illumination of the whole scene, as shown in top panel of figure 10. Notice that, although Staller (or an assistant) necessarily passed through the scene in composing the image, his body left no impression. Similarly, as shown in the bottom panel, several cardboard Poseidons topple without a hint of human intervention. Both of these invisibilities are due to blur (here: persistence) and long exposure, as in the bottom panel of figure 10. Staller's use of small light sources and very long exposures creates a kind of visual metonymy (Kennedy 1982) where, for example, the sparkler on the end of a long stick becomes motion itself and also its record of passage through the night.

[12] In such images lines may also be shown to one side or around a moving object or individual, mimicking some aspects of multiple, stroboscopic exposures. These 'quaking' lines were often initially used to indicate agitation—rapid back and forth movement. Kennedy (1982), borrowing from the literature on metaphor, called this visual example of *hendiadys*.

Figure 10. Two images by Eric Staller. That on the top is detail of *Lightunnel* (1977), created by swinging a sparkler on a long stick while passing through a deserted street. That on the bottom is *Poseidon* (1980), a cardboard full-size cutout of the Greek god rimmed with small lights, falling backward in six equally spaced building alcoves along a street (both reprinted with the permission of Mr Staller).

Second, almost all images in astronomy, be they from the visible spectrum or not, are produced with extremely long exposures. Most are produced by using a camera that follows the position of celestial bodies with the earth's rotation, gradually panning the camera. For pedagogical purposes, however, some pictures in astronomy fix the position of the camera to earthbound coordinates. Such a photograph might be taken from near the north pole (or even elsewhere) and, over the course of several hours, the motion of the earth and of the camera reveal the sweep of star paths as an array of concentric circles. These patterns effectively show the rotation of the earth beneath the night sky (eg Layzer 1984, page 24). Such patterns, revealed over time, appear to be effective in helping migratory songbirds prepare for their flight (Emlen 1975; see also Cutting 1986).

Third, time-lapsed displays have been used with great success as illustrations in the science of reading and looking. These images show the scanpaths of individuals' eye-movement behavior when looking at an image, often superimposed on the image that the viewer is looking at. The scanpaths are typically shown as a series of lines and dots, corresponding to saccades (eye movements) and fixations, indicating where and in what order the individual was looking (eg Underwood 1998; Yarbus 1967).

Fourth, consider another example from visual perception, stemming from work of Gunnar Johansson (1973, 1975) and the gait analyses mentioned earlier. The image in the second panel of figure 4 depicts the array of motion over time of a pedestrian walking from left to right. In sympathy with Staller, it is as if the camera has been fixed in position, the lens remained open, and the pedestrian walked in darkness laterally in front of it. That pedestrian, of course, is not seen full-view; instead he is shown schematically by a series of eleven lights attached to the head, shoulder, elbows, wrists, hip, knees, and ankles. Notice that only the spatial undulatory pattern of flow is seen in the image, the relations in time are not. Representations such as these have been shown to yield some reasonable information about the subject and action portrayed, and are thus useful as a scientific image; but they are vastly inferior to the moving display itself (Cutting and Kozlowski 1977; see also Beardsworth and Buckner 1981; Hill and Pollick 2000).

In addition, consider the several examples in figure 11. An extremely interesting aspect of action lines is that they are attached to the most recent depicted instant, and extend backwards in time as Gombrich astutely noted. That is, the action lines depict past action, not future action. Read this way, the image by Bragaglia at the bottom of figure 6 should be seen as Balla turning away from his painting, not turning towards it, and Marey's bird in figure 5 can be moving only to the right (which knowledge already told us). It is not clear why this should be so, but it seems unlikely to be mere convention, since the results of Burr (2000) run in only the canonical direction—lines of past motion before the current state registered in the clear image.

In an insightful analysis of the depiction of motion in various types of images, McCloud (1993) discussed how combinations of stroboscopic and action-line representations work together. Some are shown in three panels of figure 11. That on the top left shows action lines superimposed in stroboscopic shots as if with the stationary camera of Marey. Notice that the background is precise and stationary, and the runner somewhat blurred. Those on the top right show action lines superimposed on a moving image in the spirit of Balla's *Dog on a Leash* (top panel of figure 6) with a panning 'camera'. Notice that the background is blurred and streaked, with the runner now with precise outline. It would seem that either could be used interchangeably, depending on the intended focus of the image as planned by the graphic artist.

Action lines seem best when they are straight, or predictably curved as in the Abu political cartoon of the 1960s Cold War arms race and the metaphorical leap-frogging of Krushchev and Kennedy, shown in the lower right panel of figure 11. Other kinds of motions seem difficult and are less successfully represented. As a thought experiment

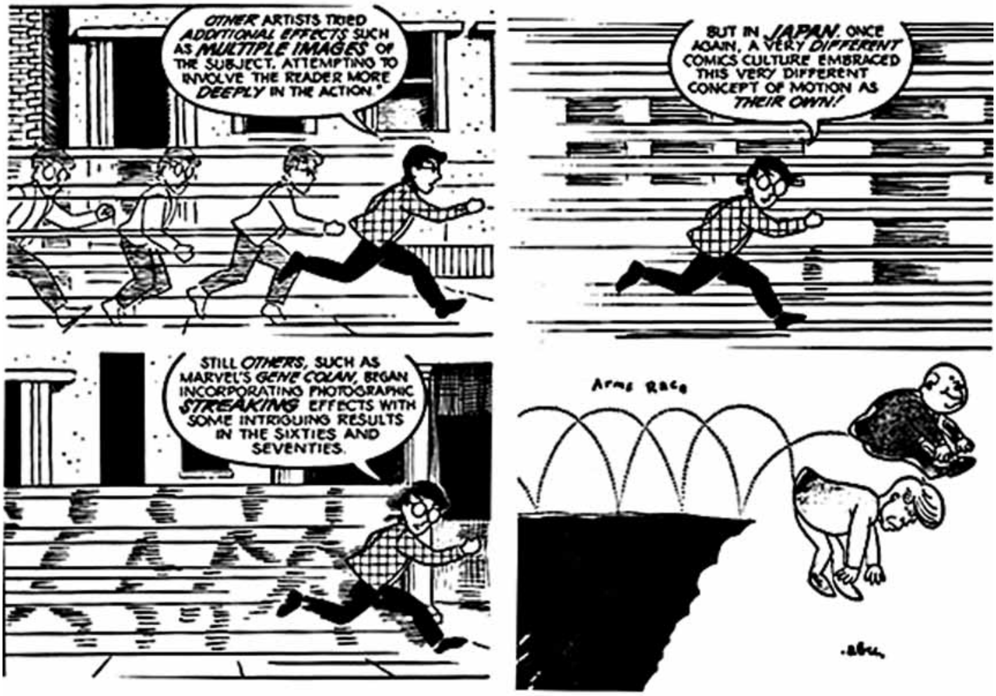

Figure 11. Action lines as representing motion. The two on the left and one at the top right, are from McCloud (1993, pages 112–113; © Scott McCloud, reprinted with permission of Mr McCloud). In the lower right is a political cartoon by Abu, showing curved action lines (*The Observer*, 11 March 1962; reprinted with permission of Guardian Newspapers Limited).

reconsider the pedestrian (second panel of figure 4). One could create a vector representation of this walker simply by showing the walker at the right edge of the display and adding rightward pointing, undulating arrows to the left edge of the display. Such additions would likely add nothing to the representative power of the image. Or one could take a snapshot of an individual walking, and then add vector corresponding to the pendular swings of the arms and legs, as suggested by the dog's mistress (top panel of figure 6) in the image by Balla. These too, I think, would not be particularly effective. Nonetheless, within the constraints of portraying relatively simple motion, action lines are equally at home in the beaux-arts, in popular culture, and in science.

Fields of action lines, or vectors, are most effective when displayed in a graded ensemble. One of the more compelling images in the vision literature is that of Gibson (1947), shown at the top of figure 12. Here Gibson, as a researcher in the war effort, displayed what is seen by the pilot in a flyby over an airfield. All vectors point away from a point on the horizon towards which the plane is headed. Indeed, Gibson's theory of wayfinding (Gibson 1966, 1979), or how we know where we are going, is explicitly contained in this image. We find our way, Gibson argued, by finding the point of radial expansion. When computer graphics generally became available, wayfinding research burgeoned. In their research, various researchers tried to show their stimuli. One example is shown in the bottom panel of figure 12. Interestingly, it violates convention and does not have the most recent instant occupying the head of each vector. Instead, the dots are attached to the tails. This makes one seem as if one is moving backward. Elsewhere, I (Cutting 2000) have discussed such images, and the general problem of representing self-motion, in more detail; and although the Gibson image is evocative, I do not think that Gibson's theory of heading determination is correct when applied to a pedestrian, which was his intent (Cutting et al 2000).

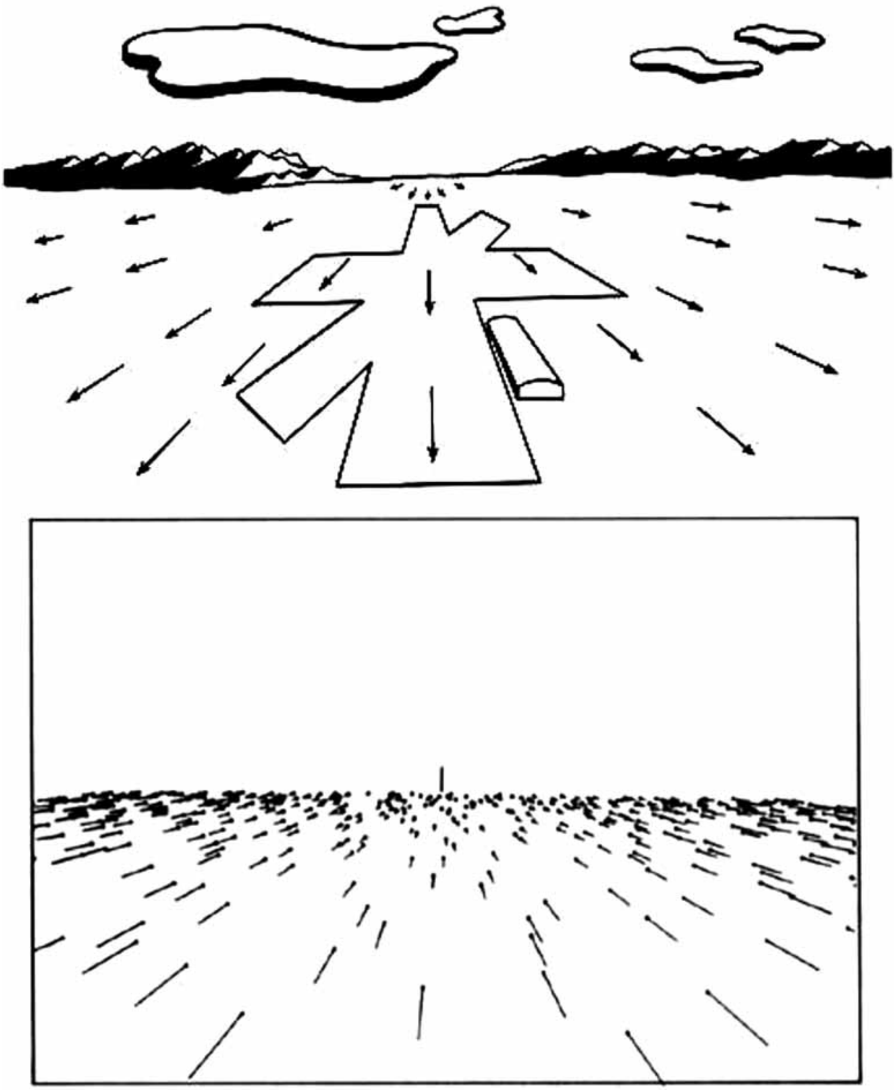

Figure 12. Optical flow as represented by Gibson (1947) and by Warren et al [1988; © 1988 by the American Psychological Association (APA); reprinted with permission of William Warren, Jr and the APA]. Note that motion trails behind the arrowheads in the upper image, but leads the dots in the lower. The upper panel follows the convention.

Action lines appear not to be as easy to understand for children as multiple images (Friedman and Stevenson 1975), and a good understanding of the motion implied seems not to emerge until around puberty. But for other purposes, suggested in table 1, the vectorial approach to the representation may be the most successful, at least in science and with regard to satisfying the four criteria. Such representations have the potential to be evocative, to depict an object or the environment clearly, and to illustrate both the direction and the extent of motion. What are its drawbacks? The most important would seem that it does not apply easily to complex situations, where vectors would point in many different directions without being smoothly related to one another.

9 Representations of motion and motion perception

A prodigious amount of research on the perception of motion has filled our journals and textbooks, almost all of it since these conventions of representing motion evolved. Are there results from the science of perception that reinforce their efficacy? Probably not. The Futurists believed that stroboscopic representations captured our visual physiology. In other words, just as film carved up the world in time, so too did our vision. Evidence may have been taken from the fact that the movies of the 1910s were true 'flicks', with flicker rates well below critical flicker fusion (eg Anderson 1996). But this is not how we normally see; we can only see stroboscopically under artificial lighting. Indeed, raising kittens in slow-strobe environments destroys their motion detection systems (Cynader and Cherenko 1976). And affine shear does not happen to real locomotives and automobiles, but the resultant forward lean does nicely anthropomorphize them, undoubtedly affording us more empathy with inanimate objects. After all, we know that we lean forward when running and walking. And we don't typically see the blur of objects in motion, owing to remarkable clean-up properties of the visual system accomplished by lateral and temporal inhibition (Burr 1980). Nor do we see action lines, although perhaps under very limited conditions (again stroboscopic) they may trigger a response similar to motion (Burr 2000; Shepard and Zare 1983). Indeed, Galileo attended summer festivals with wheels rolled down hillsides and commented both on the cycloidal arcs and the visual persistence of the curves (Rubin 1927).

To look for neurophysiological underpinnings of these motion representations, however, is surely to look in the wrong place. After all, the purpose of these representations is not to trick the visual system into seeing motion; instead, it is merely to suggest to an observer, sometimes a well-informed one, that motion has occurred. Consider some data and then a Gedanken comparison. Sperling (1976) compared the relative effectiveness of multiple-frame stroboscopic displays of dots with two-frame apparent-motion displays or dots. Viewers rated these stimuli on a scale of 0 to 10 with 0 representing no motion and 10 representing motion that was indistinguishable from real motion. Judgments of the stroboscopic displays were often near 10; the two-element displays never higher than about 3; but both diminished towards zero with greater separations in space and time. It should be clear that the representations shown in the figures of this paper would all be a clear zero on such a scale. There really is no motion. Kennedy (1982) would call them metaphors for motion.

One remarkable aspect of these representational techniques, then, is that they work at all. What makes them work? What makes them relatively easy to 'read' as motion? Almost surely our ability to understand them is served by our experience with photography, film, with the various other genres of popular culture (eg comics, television cartoons), and with motion itself. Another remarkable aspect is that this list of representational types is neither longer nor vanishingly short. In other words, all other things being equal one might have anticipated being able to make a list of twenty ways to represent motion, or even only one. Why five? That the list is not longer is probably because of severe constraints on what we can cognitively accept. This idea, however, is not easily testable since a survey of failed examples of motion representations is impossible to compile. That the list is not shorter—indeed that there is a list at all—is certainly due to the inventiveness of imagemakers over centuries. How many trials and errors were made before early artists were happy with their results? This too we will never know.

10 Summary

Dynamic balance, multiple stroboscopic images, affine shear, photographic blur, and action lines have served artists and scientists well, and are likely to do so for a long time to come. There may be other ways beyond this list in which motion can be represented in a static image, and there may be new devices and techniques that have yet to be discovered. Nonetheless, it will remain that these different representational schemes have different strengths and can be used for different artistic and scientific purposes. From the point of view of scientific illustration, however, static images with vectors seem to satisfy best the criteria outlined here—evocativeness, clarity, and revealing the direction and extent of motion.

Acknowledgments. This article is based on a lecture first presented at the 5th conference of the Académie du Midi, "Imagination and Cognition", at Tuchan, France, June 1993. At the time I was a John Simon Guggenheim Memorial Fellow. Later versions were given in series of talks given both at the Université de Genève in 1997 and at the University of Pennsylvania in 1999, and it then grew out a companion piece (Cutting 2000) on vectorial representations of optical flow. I thank James Ferwerda, Michelangelo Flückiger, Gary Hatfield, Claudia Lazzaro, Manfredo Massironi, Nicholas Wade, and an anonymous reviewer for comments.

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