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ASPECTS OF MOTION PERCEPTION

BY

PAUL A. KOLERS

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FOR

JULES V. COLEMAN

AND

GEORGE A. MILLER

WHO MADE LIGHT OF DARKNESS

Human vision is such an enormously rich complex of experiences, and human beings are so diversified in habits and interest, that no two of us value our eyes for quite the same set of reasons. If asked what aspect of vision means the most to them, a watchmaker may answer "acuity," a night flier, "sensitivity," and an artist, "color." But to the animals which invented the vertebrate eye, and hold the patents on most of the features of the human model, the visual registration of **movement** *was of the greatest importance.*

G. L. WALLS (1963, p. 342)

FOREWORD

In 1964 I published a paper that pointed to certain differences in the way the visual system implemented the perception of motion derived from physically moving objects, and illusory or apparent motion derived from flashing lights. The paper came to the notice of H. J. Eysenck, editor of the International Monograph Series in Experimental Psychology that is published by Pergamon Press. I accepted his invitation to prepare a monograph on the subject of apparent motion, but between that time and 1969 my attention was occupied by other things. At the latter date, at Bell Telephone Laboratories, I undertook the study of some aspects of motion and form perception, particularly as they relate to the quality and fidelity of electronically transmitted images. This monograph grew out of that study.

A number of problems confront the engineer interested in transmitting pictures electronically, because pictures tend to be quite detailed but the transmission medium is both limited and expensive. Hence a number of engineers actively explore the topic of bandwidth compression, seeking a means by which maximum amounts of visual information can be transmitted at minimum cost. It seemed to me that a contribution to this topic that a psychologist might make would be to study the kinds of information that people actually use in their perception of continuing sequences of briefly presented pictures, such as characterize television transmission of real scenes. Not everything in a picture is perceived, nor do people typically have to look at great amounts of detail in order to come away with an adequate representation of what they are being shown. The reason is that much of our perceiving is anticipatory and inferential; it is based on an active sampling of clues rather than on passive reception of details. What is not known, however, is whether the sampling is haphazard or whether it is rule-governed; whether, that is to say, any aspect of any object is as good a clue to its identity and is as likely to be sampled as any other. The intuitive answer to this uncertainty is a negative one; and in this regard concepts of salient or distinguishing features that characterize objects and facilitate their identification have come to the fore in recent years. Hence we may ask, what aspects of pictures best aid their recognition; what features most readily aid in distinguishing them? What are, in fact, the salient or distinctive features of pictures? Can one formalize these characteristics?

Questions of this kind motivated some of the research I shall report later in this monograph. The direction followed in seeking an answer was the classical one of dealing with simple, stripped down instances of stimuli. Although the pictures most likely to be transmitted in an electronic system are of people in movement, we began with simpler instances; in fact, with such classically simple ones as plane geometric figures. Moreover, we studied their perceptibility not when they were presented one at a time, measured for their specific geometry and luminance, but when they were presented in brief sequences. Therefore we were immediately dealing with illusory motion of the configurations, for it is a characteristic of the visual system that it perceives brief, properly sequenced presentations as objects undergoing spatial translation. It is just this characteristic, in fact, that the motion-picture projector and the television screen take advantage of, albeit in substantially different ways, in triggering those perceptions of objects in motion that we do see with those media. As we shall see below, the technological successes with those media do not depend upon a correct understanding of their effects on the nervous system; the technology works, but no currently available account of the perceptibility of forms in motion is correct. Theory lags practice rather extensively in this domain.

One outcome of our research was the discovery that the visual system actively constructs, implements, and fills in features of objects derived from a sampling of the physical presentation. The visual system does not merely record what has been presented to it (if it records that at all); it actively creates its own pictorial reality. Moreover, the mechanisms underlying this creation seem to be substantially different from the mechanisms utilized in feature analysis. What role, if any, that feature analysis plays in normal perception is not entirely clear.

These facts emerged from a study I carried out with James R. Pomerantz in the fall and winter of 1969 and published in the *Journal* *of Experimental Psychology* in 1971. Intrigued and puzzled by them, but under a deadline created by other forces, we followed through with this investigation during the early spring of 1970. Reminded by Pergamon Press of my committment to do a monograph on apparent motion, I thought that these new investigations might be embedded in the context of this old problem; for the fact is that people have been looking at motion pictures for more than seventy years, and at television screens for more than twenty-five, but the mechanisms governing these perceptions are still unknown.

Regrettably, our work does not answer all of the questions it set out to answer. Indeed, we were blocked for some considerable time, for in our thinking we continued to seek positive answers to certain questions whereas it becomes increasingly likely that some of them cannot be answered positively. Thus for conceptual and administrative reasons it was not possible to round out this work, and it is incomplete. I present it at least for the questions it raises if not for the answers it provides.

On and off between 1964 and 1968 I discussed various aspects of the perception of illusory motion at Project Zero at the Harvard Graduate School of Education. I think it was in response to those beneficent challenges that some concern with pictorial notation crept into my own thinking, although whatever distortions it may have there are not to be laid at the door of Project Zero or its director, Professor Nelson Goodman. It was during that period also that I carried out some preliminary experiments on form and motion perception at the Research Laboratory of Electronics, in connection with a course on perception and cognition I taught in the Department of Electrical Engineering at Massachusetts Institute of Technology. Moreover, as my own command of German is poor, I am indebted to several friends and former colleagues for aid with various aspects of the older literature. In particular I thank the former Misses Katharine Gilbert and Jean Mechlowitz, and Dr. D. C. Milne in this connection. I also thank Drs. David N. Perkins, Ronald Cohen and Ivan Bodis-Wollner for their comments on the manuscript. My greatest obligation, however, is to James R. Pomerantz for his conscientious, creative, and energetic contributions to our short-lived collegiality. I am not sure that I would have had the patience or subtlety to pursue these elusive realities alone; indeed he always shared and sometimes even led in the formulation of our

experiments. And of course I shall forever remember my stay at Bell Telephone Laboratories, and here record my thanks to that institution for enabling me to carry out this research.

Toronto, Ontario

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I thank the authors and the American Psychological Association for permission to reproduce the following figures: 3.6, 4.3, 4.4, 4.5, 6.2.

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CHAPTER 1

THE BACKGROUND

About 2500 years ago the mathematician and philosopher Zeno of Elea invented four puzzles regarding distance and motion which were, in Bertrand Russell's words, "immeasurably subtle and profound". The most famous of them, that the swift Achilles can never overtake a tortoise that has started a race before him, and indeed all of the other three, have finally given way before mathematical analysis (Russell, 1938, pp. 347–354; Grünbaum, 1967), but like a ghost in the machine, they still haunt proposals about the mechanisms of perception.

One interpretation of Zeno is that the perception of motion is based not on current sensory information, but on memory for position and time; hence on comparison, guess, or inference. This interpretation alleges that what our visual system actually detects are objects in different locations at different times; noting the disparity, we create a sense of motion to resolve it. Perception of objects, memory of their position, and delusion are therefore the main components, according to this theory, of our perception of motion.

Until the last quarter of the nineteenth century there was little evidence that refuted this view directly. Then, in 1875, the physiologist Sigmund Exner showed that when things are arranged properly, two brief but stationary flashes are seen as a single object in motion. The timing of events is so rapid moreover, and the perception of motion so immediate, that memory cannot be its source. Working at a time when the task of psychology was taken to be the identification of the sensory elements of perception, Exner argued that motion is not an inferred attribute of objects perceived in different places, but a basic element in the mind's armamentarium.

Aside from its philosophical implications, the import for psychology of Exner's study lies in its systematic use of what even at that time was a well-known laboratory curiosity, the phenomenon of apparent motion. To create the illusion for his experiment he exposed two spatially separated electrical sparks sequentially; when the timing was appropriate, his observers saw a single flash move smoothly across the empty space between them. Exner's interest lay less in the characteristics of this perception of motion, however, than in establishing motion as a basic sensation; thus, except for an occasional paper, it was not until 35 years later, when Max Wertheimer began his systematic work, that this old phenomenon of illusory motion was subjected to intensive and detailed study. It is worth speculating about the delay.

One possibility is technological. Creating the phenomenon for controlled study requires the use of special apparatus; electric sparks are not very good sources of illumination in visual experiments that manipulate time as a variable. Perhaps this is one reason that the phenomenon was not explored extensively; but if it is, it is not a strong reason, for many mechanical contrivances were known that yield vivid perceptions of motion (Boring, 1942). A more convincing reason for the neglect of the phenomenon lies with the intellectual Zeitgeist of the nineteenth century. The notion then current of how the mind works is in some respects different from our own. Many scientists then thought that the visual system analyzed stimuli to extract the important elements which, following Helmholtz, were called "sensations", and the mind combined these into "perceptions". Moreover, the sensations were long thought to be faithful to the reality of the physical world, representing it truly. Therefore many scientists of that period believed that perception stood in a direct relation to the objects inducing the stimulation, so that our perceptual experiences were faithful copies of the physical world. Apparent motion, however, like many other perceptual experiences, is an illusion; it is a believable perception of motion that originates in the sequenced flashing of physically stationary objects. The study of illusions did not have much respectability in an intellectual environment that emphasized veridicality of perception. As late as the end of the century the distinguished German psychologist Oswald Külpe (1893), who actually was Wertheimer's teacher, wrote of illusions that they are (in Titchener's translation) "subjective perversions of the contents of objective perception".[1] By "objective perception" he was assuming the

[1] "subjective Veränderungen an dem objectiv Wahrnehmbaren" (p. 184).

correctness of just that mechanistic philosophy that argued for a one-to-one correspondence between physical stimulation and psychological experience. The phenomenon of apparent motion is a dramatic violation of that assumed correspondence.

The perception of motion from the sequential illumination of discrete stationary objects is so compelling perceptually and so significant theoretically that hundreds of papers have been published on its various aspects in the past 60 years. I have already alluded to its significance for Exner as a demonstration that motion is a direct rather than a derived perceptual experience. In Wertheimer's hands the phenomenon took on even deeper significance; indeed, his paper of 1912 created the foundation for one of the most vigorous branches of experimental psychology in the twentieth century—Gestalt Psychology.

Consider that Wertheimer was working at a time when the Wundtian and Titchnerian form of elementarism was in full flower; this point of view derived from British empiricism in general and from the associationism of the Mills in particular (Heidbreder, 1933). The view held that our perceptual experiences are complex events analogous to chemical compounds, whose content represents the proper intermixture of more simple elements. This mental chemistry, as it was called, took as its major task identifying the basic sensory elements and the rules by which they combined. The rules of combination were thought to be known; these were the laws of association of qualities and attributes ("ideas") that the British empiricists from the seventeenth century on had worked out. The machinery of combination known, the task remaining was to identify the elements it worked on. Then, it was thought, we would have a full accounting of mental contents, the perceptions and thoughts of everyday experience.

Wertheimer, a deeply imaginative man, questioned this interpretation of perceptual processes. Perception cannot be so elementaristic, he argued; for example, what are the elements of a rhythm and how, as von Ehrenfels had pointed out earlier, could such an elementarism explain the perception of a melody despite a transposition of key that left no notes in the two forms identical? Rather, Wertheimer argued, the nervous system is a device that organizes and structures its sensory inputs; it does more than convey sensations as so many electrical signals through so many wires. The introspectionist psychologists, in insisting upon analysis and decomposition, seemed to ignore the basic characteristic of perception, that it is of whole objects segregated in space and time. The perception of motion from two stationary flashing lights is a powerful example of the organizing characteristics of the visual nervous system.

The illusion of motion can be created in many ways; in fact, there are a number of illusions of motion. The one that is most familiar to psychologists and that was exploited by Exner (1875) and studied by Wertheimer (1912) has many names, among them phi motion, beta motion and optimal motion. With present-day electronic technology, a very easy way to produce this phenomenon is to illuminate two small spatially separated gas-discharge lamps in sequence for brief controlled durations. The lamps may be viewed directly, against a dark background, or they may be used to illuminate drawings or other figures. A multichambered tachistoscope that illuminates different objects successively is a useful device for the purpose, but a computer generating displays on a cathode-ray tube (CRT), or a motion picture projector can also be used. So too can a stroboscope that intermittently illuminates a physically moving object. Each method introduces slight variations in the data that are obtained, for each method creates its own artifacts, but all share the ability to create a perception of motion from stationary objects illuminated in sequence. Wertheimer (1912), who was the first to recognize many of the psychological and philosophical implications of the phenomenon, did his own experiments mainly with a tachistoscope, and a borrowed one at that.

With great ingenuity Wertheimer analyzed many constituents of the phenomenon. His experiments established the paradigm for most of the later research, and many later papers worked out in detail conditions and effects that he first described. He was, however, not always correct in his conclusions.

One might think that the great amount of work expended on the perception of illusory motion would have left little that was new to add. In point of fact, however, the phenomenon has never been satisfactorily explained. Although several lines of theory have been advanced and explored, none fully accounts for the facts in a detailed way. Indeed, in the hands of the Gestalt psychologists the phenomenon was principally a vehicle for advancing their philosophy; in life, its major occurrence is on the motion picture screen, and on advertising signs that when properly flashed seem to move. Does so behaviorally trivial a phenomenon have any significance in the modern world? Is the phenomenon still worth investigating? And if so, why?

My answer is obviously affirmative on all counts. The basis of the affirmation is the recurring similarity of the data obtained in the study of illusory motion to data obtained in other studies of visual functions. Although illusory motion itself occurs infrequently in our daily lives, its occurrence seems to depend upon the action of mechanisms that are centrally involved in all perceptual experience. Man depends heavily upon his visual apparatus as the source of much of his information. It should be obvious that the better we understand how his visual apparatus works, the better we are able to evaluate and understand other related forms of information processing. The study of man's characteristics as an information-processing organism is the object of a large segment of contemporary psychology.

A related reason for the affirmation is that the phenomenon of apparent motion speaks to the broad issue of the means by which man represents to himself the characteristics of the world outside his own skin. Earlier philosophers and psychologists believed that the representation was quite straightforward and faithful to physical reality. We now know that this view is too simple; we substitute for it the view that man samples his environment, and on the basis of samples constructs a representation that may be more or less consensually verifiable. Wertheimer used the phenomenon of apparent motion to demonstrate some of the ways the nervous system organized stimulation it receives; its further analysis reveals much about the interplay in perception of environmentally-supplied and self-supplied information.

In the early chapters of this book I shall summarize some of the major findings about illusory and veridical motion and the theories they have generated. The central section of the book describes a number of experiments J. R. Pomerantz and I carried out to evaluate some of the theories. Regrettably, all the theories are invalidated. In later sections it will be shown that a two-component model of motion perception is required, but that even this is not fully adequate to the facts. In the final chapter I shall discuss some characteristics of the status of perceptual experiences, and show there that the visual system seems to contain two relatively independent means of representing experience pictorially.[2]

Before proceeding, however, it is necessary to distinguish between illusory and veridical perceptions on certain grounds, if only to explain the use of the words. We mean by "veridical perception" that information we acquire through one sensory channel is consistent with information we acquire through another; or that what we expect on the basis of acquired information can be tested by action; or, sometimes, that what we perceive is not entirely idiosyncratic but can be perceived by other people as well. Consensual verification is one test of veridicality. We refer by "illusory perception" to an experience that can be taken as an instance of something else. Information obtained by one means allows us to make predictions about consequences or concomitants of our experience; when these are not borne out, we define the perception as illusory. An object that seems to be moving should collide with objects in its path or should pass reference markers in a particular way. Failure to do so reveals that the object seen only mimics some of the features expected of the veridical perception, hence is illusory.

Illusions are illusory just because they share some notable features with events they mimic. Lacking certain crucial features, they do not make a perfect "fit" with our implicit theory of the world. It should be obvious, therefore, that appearance alone does not usually distinguish between veridical and illusory perceptions, for the illusion consists just in the fact that there is a compelling similarity of appearance between them. Hence careful analytical tests are often required to establish whether a given experience is illusory or not. Judgments of "reality" and truth cannot be reliably based on appearance only; they require confirmation from tests outside the experience itself, for an event cannot reliably be used to evaluate itself. By "veridical", therefore, we mean consensually verifiable to the limits of possible tests; and by "illusory" we mean looking like the veridical but not similarly verifiable. These are clumsy distinctions at best, but are necessary to keep in mind hereafter.

[2] Throughout, I use the words object, contour, shape, and figure in approximately synonymous sense to refer to what is perceived. Speaking strictly, of course, figure, shape, color, motion, and the like are all aspects or properties of the perceived object. In the same loose way I use "pictorial experience" as synonymous with visual perception.

CHAPTER 2

WERTHEIMER'S CONTRIBUTION

WERTHEIMER'S paper of 1912 reported an astonishingly large number of effects. His ingenuity in testing the limits of the phenomenon of apparent motion and of devising critical tests for hypotheses was very great indeed. The paper not only launched the movement that became Gestalt Psychology, it also established the paradigm that is still followed in many studies of apparent motion. The paper is systematic, ingenious, and interesting, one of the great ones in the experimental psychology of visual perception. It is fitting therefore to begin by summarizing some of the ideas that exercised Wertheimer, and the demonstrations he made in response to them.

The argument that Wertheimer inherited from Exner (1875) was that movement is a sensation in its own right, one of the basic constituents of perception, and not a derived or computed one. Exner's affirmation of this idea was based on one of the first serious investigations utilizing apparent motion. (The idea itself was supported by several other contemporary investigators, whose work Boring (1942) has summarized.) Exner wished to measure the threshold for temporal succession. For the purpose he exposed two spatially separated electric sparks in sequence, varying the interval between them. He found that at temporal separations of about 45 msec the observer could regularly report the physical order of the flashes, but if the distance separating them was not too great, the observer perceived not only their order but motion between them. Exner then went on to measure the lower threshold for this effect, and found that observers attributed a direction to the perceived movement when the two flashes were separated by as little as 14 msec; and this occurred even though at these temporal intervals but at wider spatial separations their order could not be reported correctly.[1]

Exner showed, therefore, that three distinct perceptual events can be established with brief properly sequenced flashes. When the temporal separation is 10 msec or so the two flashes appear simultaneous; at somewhat longer separations they appear as a single object in motion; and at still longer separations they reappear as two flashes but in succession. The perception of motion, he found, occurred at shorter temporal intervals than were required for a perception of sequence or order. Therefore, Exner argued, memory of position and perception of order cannot be the basis of the perception of motion. Having made this telling point, Exner went on to other things, and the phenomenon itself was little explored for 35 years.

Between Exner's work and Wertheimer's, which began in 1910, the motion picture camera and motion picture projector were invented. Here were devices that yielded complex perceptions of motion indeed. The projector works by illuminating successive frames of film at a fixed rate, a shutter interrupting the beam of light while the film moves. The sequence projected on the screen is always therefore physically stationary, for the motion of the film is not itself projected. (If it is, by eliminating the shutter, one sees only smears of contours and shades.) According to one legend it was in contemplating the physiological and psychological aspects of the motion picture—the perception of motion from discrete presentations—that Wertheimer became interested in the phenomenon of apparent motion.

For his experiments, he simplified the situation drastically. Rather than with complex scenes, he began his investigation with a limiting case, two horizontal lines, or a horizontal and an oblique line, exposed in sequence. He readily found Exner's three stages when he varied the temporal interval between the lines. When the interval is very short, the two lines appear simultaneous and, when one is oblique, as forming an angle; when the interval is long enough they are seen in succession; and in an intermediate range they are seen in optimal movement: one

[1] The values are in rather good agreement with those found by recent investigators using more refined apparatus. See Hirsh and Sherrick (1961) for the perception of order, and Thorson, Lange, and Biederman-Thorson (1969) for direction of motion.

line appears to move through the physically empty space from the first position to the second. Wertheimer set himself several questions to answer.

The main question was whether he could clarify the emergence of optimal apparent motion—the perception of an object moving through the phyiscally empty space between the origin and terminus—from simultaneity at one end and succession at the other. He proposed to study this by varying the temporal interval between the flashes in small steps. Another question concerned the epistemological and perceptual status of the illusory object. He studied this in part by interposing other stimuli into the regions through which the illusory object moved. A third question was the way in which set and attitude affected the illusion. This he studied by varying instructions to the observer, to affect the location of eye fixations and what Wertheimer called the posture or attitude of attention. And finally he studied some aftereffects, but with a radically different kind of display from that used in the foregoing, a rotating arithmetic spiral. Except for the last tests, the main variables were the spatial and temporal characteristics of the flashes, whose duration and distance apart were manipulated. He also varied their configuration, but not in the same systematic way.

Wertheimer's experiments revealed quickly that the three stages Exner had described could be supplemented to include partial motions, and phi or objectless motion. The partial motions were characterized by a seeming movement of the first flash part way across the screen, where it disappeared, and the appearance of the second flash displaced from its true location but seeming to move toward the terminus (see Fig. 2.1). Phi motion, which was given the greatest theoretical attention, was described as a sense of motion without a concomitant perception of moving objects; its closest analog in physical terms would be an object that appears at one location, disappears at another, and moves so rapidly between them that only its motion but not details of its shape or identity can be made out.

A word on nomenclature is needed before proceeding. The term "phi phenomenon" or "phi movement" is sometimes used generically for illusory motion. This is misleading usage, for phi motion correctly refers only to global "figureless" or "objectless" apparent motion, analogous to the very rapid passage of a real object across the field

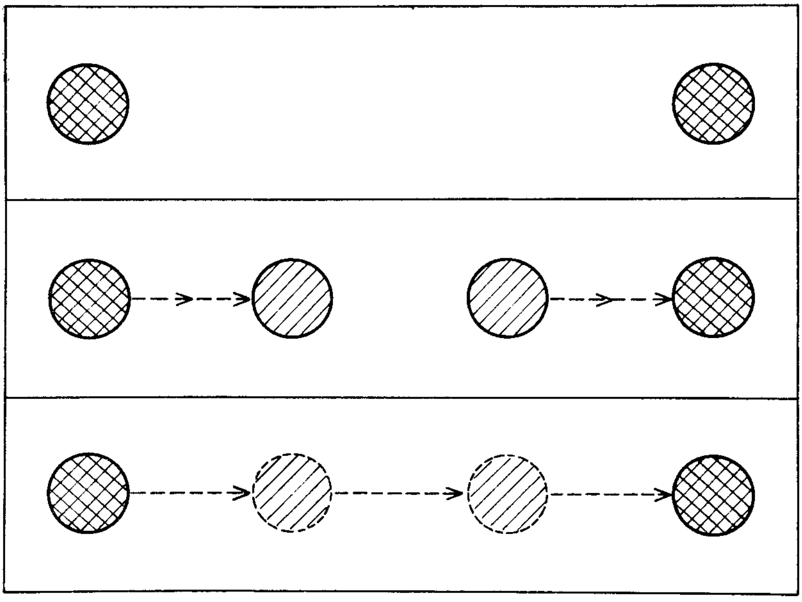

Fig. 2.1. At rapid rates of flashing, two lights are seen in place ("simultaneity"—top panel); at the proper slower rate, a single light appears to move from its first location smoothly and continuously across the screen to the second location ("optimal movement"—bottom panel); and between these two rates, a light seems to move part-way across the screen, disappear, reappear at a more distant point, and continue on to the second location ("partial movement").

of view too quickly for its contours to be made out. Beta motion, on the other hand, refers to the perception of a well-defined object moving smoothly and continuously from one location to another, analogous to the slow passage of a real object across the field of view. "Optimal motion" is synonymous with beta motion. I shall use the terms phi, beta, and optimal motion in these senses. Recently, however, Kinchla and Allan (1969) have used the term "phi" to refer to still another aspect of motion perception, one unrelated to the terms discussed here. Their usage should not be allowed to confuse the issues further.

Phi motion was given the greatest theoretical attention because its occurrence seemed to prove conclusively that motion is not a complex