

# Toward an Ecological Field Theory of Perceptual Control of Locomotion

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The field concept was introduced into physics in the 19th century. Soon afterward, some Gestaltists tried to use this approach to characterize the internal global brain process. Conversely, another Gestaltist, Lewin (1938), tried to develop a field description of the physical and social environment in which the brain field was immersed. Later, J. J. Gibson (Gibson & Crooks, 1938/1982) attempted to conceptualize the environment–organism interaction in field theoretic terms. First, he suggested that a dynamical field of safe travel may be used by drivers to control their automobiles in traffic while avoiding collisions. Later, Gibson and his colleagues (Gibson, 1950; Gibson, Olum, & Rosenblatt, 1955) showed, mathematically, how an optic flow field that actors may use in selecting approach paths for landing aircraft safely is available. Over the ensuing decades, the optic flow field description has provided a powerful and popular tool for addressing a number of diverse problems in visual perception as it pertains to the control of action. Although in a seminal article, Gibson (1958) outlined a general theory of visually controlled locomotion, a recently published special issue on this topic (in *Ecological Psychology*; W. H. Warren, 1998) revealed that in even simple tasks (e.g., steering), intentional and informational constraints are still not yet understood.

This article critically reviews the history of field theoretical approaches to the problem of perceptual control of goal-directed behavior. In particular, our overview focuses

on the historical sources and development of Gibson's field theoretic attempts to address the visual control of locomotion. Our overview also provides an evaluation of recent field theoretical efforts to describe animal–environment interactions. We conclude that the use of interaction fields seems to be the most promising current approach. Because these fields incorporate both perceptual and action variables, they provide a natural way to formulate the perceiving–acting cycle as the reciprocal interplay of information and control along a goal-directed path. Finally, field theory, we suggest, provides an important tool because its power can be readily extended to include other useful techniques as well (e.g., quantum mechanical path space formalisms).

The trademark of modern sciences is that they are mathematical. Arguably, the measure of maturity of a science is the mathematical formalism its theories are using. At the same time, modern sciences are empirical. Consequently, any scientific discipline can be evaluated along these two dimensions of degree of mathematical expression and amount of empirical support. Physics is generally recognized as having achieved the highest degree of balance in these two ways. Perhaps, this is why it is often considered as the role model for less developed sciences such as psychology.

As a relatively young science, psychology has developed the empirical whereas the mathematical has received less emphasis. Certain paradigms of psychology, however, have aspired to correct this imbalance: learning theory, psychophysics, and measurement theory, and more recently, cognitive science and ecological science come immediately to mind.

A primary obstacle to mathematization of a science is selection of a suitable conceptual basis for the formalism, one that makes the formalism necessary rather than merely convenient. For example, for cognitive science, network theory is proving useful but has not yet been fully explored.

This article will explore the question of what formalization is best motivated by the fundamental issues of ecological psychology (Iberall, 1995; Kadar & Effken, 1994; Shaw & Kinsella-Shaw, 1988; Turvey, 1992). The answer that seems best, given that the history of this field is intertwined with that of Gestalt psychology, is mathematical field theory.

In this century, there has been a dramatic shift away from classical mechanics, the ruling physical paradigm up until the end of last century. This radical change may best be characterized by the emergence of field theory. Together with quantum physics, and Einstein's theory of relativity, field theory revolutionized physics. This new development did not discard classical mechanics, but it did relegate it to a narrower sphere within the total picture given by these three theories. Field theory was the first and most important of the three because it paved the way for the other two. Perhaps that is why field theory had the most influence of psychology, although all three of these theories have left their mark. Yet field theory in psychology is still in its infancy.

Of what use is field theory for psychology? Although the concept of *field* is not uniquely defined in psychology, we can use Lewin's (1951) definition as a rudimen-

tary one: "A totality of coexisting facts which are conceived of as mutually interdependent is called a field" (p. 240). Lewin borrowed this concept of field from Einstein. It is not essentially different from the attempt of Gestalt psychology to view the whole as distinct from its parts. Ehrenfels (1890) brought the whole-part relation to the attention of psychologists with his now famous example of a melody. He noted that a melody is not a mere sum of the individual notes. For instance, despite transposition of key so that every constituent note is changed, one can still recognize the sameness of a melody as a whole. This is a clear indication of the distinct nature of the whole as opposed to its constituent parts. However, there is another important property of the field concept to be appreciated. Before the field concept was introduced in science, the mechanistic view of Newtonian physics could treat only interaction by direct contact between atomistic units—with the exception of Newton's gravitation, which allowed *action-at-a-distance*, a concept that disturbed even its author. In psychology, especially in visual perception, it was clear that direct mechanical contact was not a viable option for explaining how distal stimuli are detected. Obviously, we can see objects around us without having direct mechanical contact with them. Rather we are in epistemic contact with the environment through different fields (visual, acoustic, etc.). Although we do interact with the environment through a direct physical contact (stepping on the ground), it is our epistemic contact (through distal information detection) with the environment that enables us to anticipate the required neuromuscular control. These two aspects, the whole-part relation and the new perspective on interaction, are crucial for understanding the fundamental problem of motile organisms with perception, that is, their ability to control their behavior by perceptual information. This issue is still an unsolved problem in psychology. This article reviews the history of field theoretical approaches to the problem of perceptual control of goal-directed behavior. In particular, our overview focuses on the historical sources and development of Gibson's field theoretic attempts to address visual control of locomotion. In addition, our overview should help in evaluating recent field theoretical efforts to describe animal-environment interaction. Although most current attempts are mere revisions of earlier ones, there exist promising new directions for future research. In particular, the use of interaction fields seems to be the most promising trend because these fields are able to capture both perceptual and action variables in their reciprocal interplay of information and control along a path.

### THE EMERGENCE OF FIELD THEORY IN PHYSICS

The classical physics of Newton is based on atomistic, mechanistic principles. The world consists of objects composed of elementary pieces, called *atoms*. Under this view, change is attributed to forces arising from the collision or other direct contact of particles, whether macroscopic or microscopic. Although Newtonian physics provided scientists with enormous explanatory and predictive power, some prob-

lems remained unsolved, one of which was gravity. Gravity defied explanation within this paradigm because it manifested itself as action-at-a-distance, that is, as one body exerting force on another body without having direct contact. Newton could find no other solution for this fact except divine intervention. The need to resolve the problem of action without direct contact became even more pressing with the discovery of electromagnetism because electromagnetism provided more complex action-at-a-distance than gravity.

The introduction of field concepts into physics provided a means to resolve the action without contact puzzle. Because a basic understanding of field concepts is crucial to our discussion, a brief, technical digression is warranted. The first major step toward field theory was the recognition that energy can be transmitted through space, not only by direct contact. The *through space* phrase means that energy is distributed and operates in space. Energy can be either mass based (the classical Newtonian notion of momentum exchanged by collision) or it can take a massless form (Einstein's view). The concept of energy, thus, provides a transition from the Newtonian physics to modern physics. A major impetus in the development of field theory, as regards the distribution of energy in space, emerged from the physics of fluids and gases. The first successful treatment of this issue was due to Euler:

A field in mathematical physics is generally taken to be a region of space in which each point (with possibly isolated exceptions) is characterized by some quantity or quantities which are functions of the space co-ordinates and of time, the nature of the quantities depending on the physical theory in which they occur. The properties of the field are described by partial differential equations in which these co-ordinates are dependent variables, and the space and time co-ordinates are independent variables. In Euler's hands, hydrodynamics became a field theory, the field of motion of a fluid being characterized by the velocity of the fluid at each point, and the motion being described by partial differential equations involving the velocity components  $U$ ,  $V$ ,  $W$ , at the point [with the spatial coordinates]  $x$ ,  $y$ ,  $z$  and time  $t$ . (Hesse, 1961, p. 192)

Despite the pioneering work of Euler, today we consider Faraday (an experimenter) and Maxwell (a mathematician) as the founders of field theory in physics. Faraday discovered the lines of the magnetic field, the curved path of which led him to conclude that the medium between the two poles must itself have certain qualities. This discovery resulted in the conception of a field as the distribution of energy in empty space. In 1831, Faraday's experiments with magnetic fields led to the discovery of electromagnetic induction. This phenomenon is of interest because, to develop a field approach for the perceptual control of action, a rather similar technique is needed. For this reason, these developments will be described in some detail.

Hans Christian Oersted, a Danish physicist, was the first to link electricity and magnetism. In 1819, he noticed that a magnetized compass needle is sensitive to the effect of electric current flow in a nearby wire, meaning that electric current induces a magnetic field. If a straight wire is assumed, the induced magnetic field can

be represented by cylindrical surfaces, or concentric circles at every cross section orthogonal to the wire. The direction of electric current determines the direction of magnetic field lines by the so-called right-hand rule (Figure 1a): Grasp the wire with the right hand in such a way that the thumb is pointing in the direction of the current, then, the fingers encircle the wire in the same direction as the magnetic field lines.

Oersted, then, showed that electric current can induce a magnetic field. Faraday asked whether there exists a reciprocity, that is, can a magnetic field induce an electric current? Because he used only steady state fields, Faraday's search for this effect in the 1820s was unsuccessful. In 1831, however, he discovered that a time-

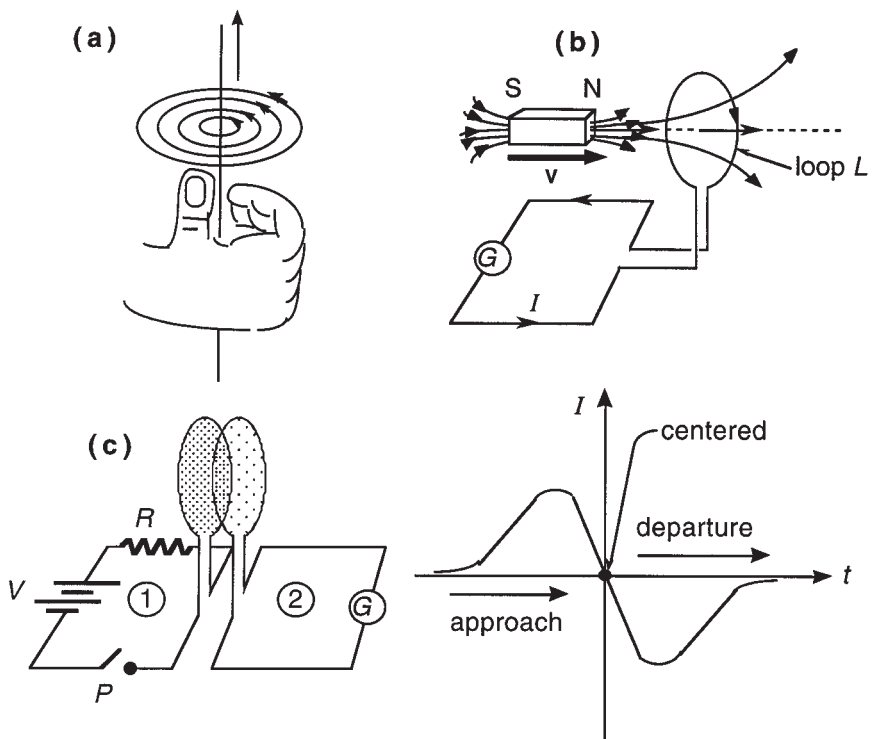


FIGURE 1 (a) The direction of electric current determines the circular direction of the induced magnetic field by the right hand rule. (b) Faraday's experimental apparatus: A closed wire with a galvanometer (to measure electric current, if any) and a bar magnet. If the bar magnet is moving through the loop measurable electricity will be induced. Moving the magnet through the loop the direction of the induced current will change after the magnet's center gets beyond the plane of the loop. (c) Two electric circuits (with a changeable resistance,  $R$ , in Circuit 1, and a galvanometer,  $G$ , in Circuit 2) can interact through their magnetic fields. Changing the intensity of current in one electric circuit changes the intensity of current in the other as well, an effect known as *mutual induction*.

varying magnetic field can produce electric current. Figure 1b illustrates Faraday's experiment. Faraday also discovered that two electric circuits can interact through their magnetic fields. Specifically, he used two electric currents with a galvanometer (G) in Circuit 2 and a changeable resistance (R) in Circuit 1 as an apparatus (Figure 1c). As he changed the intensity of current in one electric circuit, the intensity of the current in the other circuit was influenced as well, an effect is known as *mutual induction*. At about the same time, Joseph Henry discovered that *self-induction* also occurred, that is, a changing current in a circuit induces an electromagnetic field effect in the circuit itself. These seminal experimental results cried out for a unified theoretical account. Finally, Maxwell integrated the various discoveries into a universal theoretical framework, as the theory of electrodynamics.

The conjugate relation between electric currents and magnetic field lines proved to be equally useful in the study of other types of fields. For instance, in two-dimensional, rotation-free, ideal fluid flows, the flow of fluid particles can be represented by two orthogonal sets of functions. The shape of these families of functions can be derived from the boundary conditions of the flow field. In other words, the flow can be defined on the basis of the boundary contours of the flow.

The emergence of field theory in physics provided a new way to capture formally the relation between two distant phenomena. In particular, the interaction between two entities was compelling. The analogy that can be drawn between physics and psychology is transparent. Traditionally, perception was considered a detached distal connection between the perceiver and the perceived. Similarly, the concept of intentionality implied a teleological link between an actual situation and an intended future condition. These and several other problems left scientists with a puzzle to resolve that was similar to the problem of action-at-a-distance in physics.

## GESTALT PSYCHOLOGY AS FIELD THEORY

### Founders of Gestalt Psychology

At the end of the last century, Ehrenfels (1890) observed an important phenomenon in auditory perception by noting that to appreciate a melody, one must be aware of both the single tones and the whole sequence of the tones at the same time. The individual tone has its meaning only within the whole. Von Ehrenfels also recognized the relative independence of the melody, noticing that when there is a change in the pitch of individual notes, the melody is still perceived as the same. In other words, Ehrenfels discovered two criteria of the Gestalt phenomenon: (a) that the essence of a melody lies in its totality (Gestalt quality) and (b) that certain transformations do not affect the perception of a melody (transposability) in the same way.

Wertheimer, Köhler, and Koffka, the founders of the Gestalt movement, wanted to apply Gestalt concepts to perception in different modalities. The theo-

rists recognized that field concepts were especially useful in explaining the basic Gestalt principles, including the part–whole relation. Köhler (1958) argued that a theory of perception must be a field theory, basing his explanation on brain processes:

Hence we understand that the neurological functions and processes, which are bound up with perceptual processes, are localized in each case in a constant sphere; and that the processes in one part of this sphere exercise an influence on the processes in other regions, this influence being directly dependent on the properties of both in their reciprocal relation. (p. 48)

Although early Gestaltists took the brain physiology (internal field) explanation for granted, this approach remained problematic. Here we focus on the intrinsic problem of this approach, the relation between the internal field and the percepts, which is analogous to the relation between field and objects. This issue was also problematic in physics. How may a field and extended objects in that field be related in field theory?

In elaborating a universal field theory, Einstein (Einstein & Infeld, 1938/1986) realized that ordinary objects (extended masses) provide difficulties for a field theoretical perspective. The difficulty is not conceptual but technical (more specifically mathematical); nevertheless, it is the source of several empirical problems as well. In Einstein's view, objects were infinitely concentrated fields that formally determine nonintegrable singularities in the field of space. (The objects carry their own field, called *self-fields*, which cause infinities when one attempts to sum them under the surrounding environmental field). The existence of such singularities poses a serious theoretical problem that cannot be ignored. It is hard enough to deal with analytic singularities in mathematics, but the potential incompatibility of fields with objects suggests deeper problems for theoretical physics.

Furthermore, the distinction between fields and objects creates a dichotomy and a tension between a traditional object-based view and a new field-theory-based ontological perspective. The object versus field problem appears in several forms in Gestalt psychology. For example, Köhler (1958) described percepts that correspond to objects in the world and are related to each other by their *outfields*. An outfield is like a halo around the objects. These surrounding fields, according to Köhler, interact with each other:

It was our intention to explain why percepts at a distance have an effect on one another. This is only possible, we assumed (and we followed Faraday in doing so), if the individual percept has a field and if the field, which surrounds a percept, does not merely reveal the presence of this percept but also presents its specific properties. (p. 66)

Köhler's view reflects the opinion of the majority of Gestalt psychologists. One can, however, play the devil's advocate and raise a few questions: What is the elemen-

tary unit of analysis of the physiological perspective? What is the minimal whole within which we can investigate the complex interaction of parts or subunits? What is the status of the subject as a specific object? All of these questions are only variations on the same problem: What are the units of analysis, and what is the minimal framework for a whole that can be isolated from the rest of the world?

Shaw and Turvey (1981) highlighted the shortcomings of Gestalt theory, arguing that Gestalt theory lacks theoretical closure. To remedy this shortcoming, they suggested an alternative model, a type of mathematically closed system called a coalition. Lewin, one of the most prominent and influential Gestaltists, noticed these problems, too, and discovered an even more fundamental problem. Although his criticism was directed primarily at traditional psychology, Lewin's remarks apply equally to Gestalt theory.

### Lewin's Hodological Space

Lewin criticized traditional—or as he called it, *Aristotelian*—psychology for taking the individual person as an elementary, indivisible unit of analysis. Claiming that the individual person is the indivisible unit of analysis in psychology, he argued, is just as wrong as claiming that the atom is the indivisible unit in physics. Rather, in psychology, as in physics, one must look for more elementary units. Commenting that general statements, such as “All children are . . . ,” have never led to laws, he pointed out that Galileo would never have arrived at his law of free fall if he had started with the generalization “All stones are falling . . . .”

Furthermore, Lewin suggested that in psychology, laws of perception, learning processes, and so on, are probably founded on events and forces that cannot be viewed legitimately as qualities of persons in general. Rather, it is the variability of these qualities over persons and situations that make them subject to lawful regularities. These remarkable observations make it worthwhile to take a closer look at the major features of Lewin's field theoretical approach to psychology before drawing conclusions about the validity of the Gestaltists' brain-field theory.

Kurt Koffka (1935, p. 40) provided a model of the conceptual framework of Gestalt psychology as represented in Figure 2a. Here G represents the geographical environment, which is independent of the person (participant). The geographic environment produces a so-called behavioral environment in the perceptual organ, which leads to phenomenal behavior at the level of consciousness (such as experiencing aesthetic feelings, or taking perspectives within a subject centered reference system). Closure is finally achieved by real behavior, which reacts to situations in a geographical (real) environment. In this theoretical model, the real organism is the fundamental unit that supports the entire process.

In contrast to this schema, Lewin draws a different picture (Figure 2b). In his view, the geographical environment is not important, because we act in the perceived environment and not in an objective, absolute physical environment. Lewin

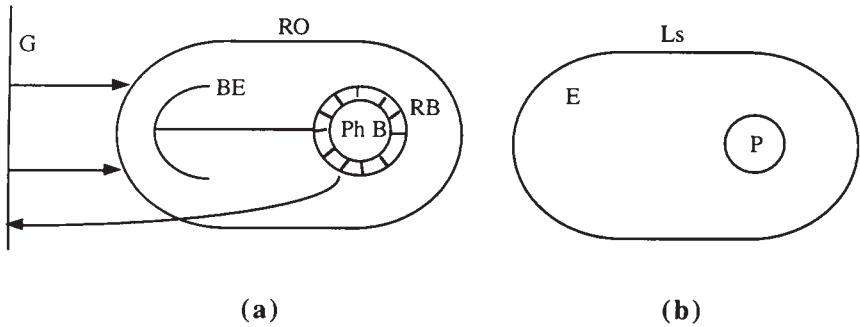


FIGURE 2 (a) Koffka's schema: Real organism (RO) in a geographical environment (G), which is independent of the person (participant). The geographic environment produces a so-called behavioral environment (BE) in the perceptual organ, which leads to phenomenal behavior at the level of consciousness. Real behavior (RB) reacts in the geographical (real) environment. In this theoretical model, the real organism (RO) is the fundamental unit that supports the entire process. (b) For Lewin's schema, the geographical environment is not important. Lewin suggested a new term, *life-space* (Ls), which is neither the geographical nor the behavioral environment. P = person; E = environment.

suggested a new term, *life-space* (Ls), which is neither the geographical nor the behavioral environment. Rather it is a subjective, perceived environment. In this framework, the behavior is a result, or function, of the person and the person's perceived environment:

$$B = F(P, E)$$

The Ls is the subjective environment with the person in it, or put differently, behavior is a function of Ls:

$$B = F(Ls)$$

Lewin's Ls is not the "here and now" space that changes continuously as a person moves about, but the integration of different regions of space (e.g., workplace, family life, activity with friends, etc.) replete with subjective feelings and evaluations. Consequently, the Ls is a sum of different regions through which, in real life, a person can move.

In Lewin's model, the person has an internal structure (although it is suppressed in Figure 3). However, what types of field may capture Lewin's conceptualization? Lewin prefers Einstein's definition of *field* as a totality of mutually coexisting facts. For the field concept to apply in psychology means that behavior must be derived from a totality of mutually coexisting facts. However, what would constitute such a totality? Even under extreme conditions, the human personality is a totality and reacts as a whole; that is, the personality can, at the same time, be viewed as struc-

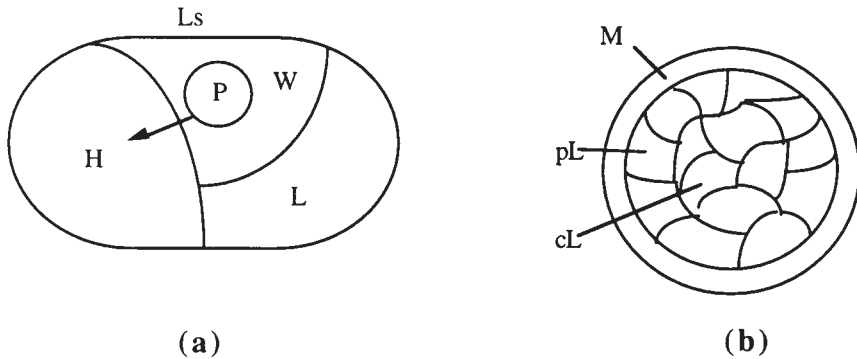


FIGURE 3 (a) The life-space ( $L_s$ ) is a sum of different regions. A person ( $P$ ) moves from region to region (e.g., from work place [ $W$ ] to home [ $H$ ] and recreation [ $L$ ]). (b) In Lewin's model, the person has an internal structure: motor-perceptual region ( $M$ ), peripheral layers ( $pL$ ), central layers ( $cL$ ).

tured from within and, even more important, as coupled to the environment. The individual person is embedded in other relations of interdependence, and it is in these that we must look for the source of the laws of field theory. Here we give a brief account of Lewin's theory, paying special attention to certain relevant features.

One immediately notices that Lewin refers to a specific type of space, a so-called hodological space, rather than a field. Why did he do so? Apparently, Lewin (1936, 1938) was trying to provide a universal methodology for psychology as Galileo did for physics. In his two monographs, he outlined a generic theoretical framework. He desired a high level of formal abstractness to ensure generality, while providing a formal structure that was both appropriate and useful. Lewin was familiar with the formal mathematical systems available at the time but failed to find one that suited his purpose.

Lewin had two major requirements for the proper structure. First, behavior is always directed either toward a goal or away from some dangerous region. Consequently, there is a need for directed entities (e.g., vectors). Second, practically speaking, it is difficult to distinguish between points in certain regions of a physical space. Thus, it would be practical for the behavioral space of psychology to treat regions rather than points as elementary units. To do so, some kind of partitioning of points into regions would be required. Lewin did not find standard geometric spaces (e.g., Euclidean, Riemannian) appropriate because directionality is not an intrinsic property of these spaces. On the one hand, field theory allows for directionality (in the form of attractors, repellers, and gradients) but provides no support for the partitioning requirement. Because fields are, by definition, compact, they are infinitely divisible into sets of points whose members are subsets of points containing still other subsets, *ad infinitum*. On the other hand, contempo-

rary theories of topology could provide support for the partitioning requirement but not for the directionality requirement.

To overcome these difficulties, Lewin (1938) introduced a new kind of structure, the hodological space, which he characterized as a new kind of geometry. Hodological space is a space divided into nonoverlapping regions. The points in any of its regions are indistinguishable. This new abstract structure—a mixture of geometry, field theory, and topology—was required because of Lewin's generic approach. Lewin himself never excluded the possibility of using other structures than hodological space for specific applications:

It might be possible, for instance, for psychology to use geometry in which the concept of distance plays a more fundamental role than it has in hodological space. ... At the present the question as to which of the possible geometries will be the most adequate for psychology is rather premature. The important task, as I see it, is to find some kind of geometry which is sufficiently adequate. To my mind, hodological space is such a geometry. (Lewin, 1938, p. 56)

Lewin had many followers who were ready to apply his theory. So many applications were found in social psychology that he is often considered as one of the fathers of social psychology (Mey, 1972). However, here we must focus on some remarkable features of Lewin's theory in a less abstract application, the description of behavior. For instance, if the underlying space is a real physical space, the abstract Ls can take a simpler form. Consider briefly some of the key concepts in Lewin's work.

The titles of his monographs indicate that the two major concepts in his theory were (a) hodological space and (b) psychological force. We have already given a brief account of the notion of hodological space. The notion of psychological force is equally important because many other key concepts are directly related to it. For example, force is (by definition) specified by direction and magnitude. Direction can be related to properties of the environment that either attract or repel the organism, what Lewin (1938) called *positive* or *negative valences*, respectively. The strength of psychological force can be related to valences, even though valence is not the only factor defining it. Distance is inversely related to the strength of the force. Also, the intensity of valences are not purely objective. The intensity of a need is positively correlated with the strength of the valence. That is, the intensity value of a valence changes with the intensity value of need (Lewin, 1938, p. 89). In Lewin's view, direction and strength of psychological forces are locally defined; and the magnitude of psychological force is velocity-dependent, as opposed to physical forces, which are linked to acceleration.

The concept of *path* also can be derived from psychological forces. Forces can be viewed as gradients of a field, and optimal paths defined as the integration of gradients, as in physics. The issue of action-at-a-distance is implicit in the notion of an optimal path between points (regions). Lewin (1938) also noticed that optimal paths, which he called *distinguished paths*, can only be defined functionally. For instance, he mentioned that there may be different distinguished paths for looking,

for walking, and for flying from one point to another. Conjointly, forces and their directions can differ somewhat under functionally different conditions (pp. 27–28).

Lewin was an influential thinker and the key ideas of his generic theory transcended Gestalt psychology. He had strongly influenced the ideas of several prominent researchers including the neobehaviorism of Hull and the ecological psychology of James Gibson. Because Gibson's theory is often mistakenly labeled as a neobehaviorism, it is worthwhile to contrast Hull's goal–gradient field approach with Gibson's field theories.

### FIELD THEORY IN NEOBEHAVIORISM (HULL, 1952/1964)

Clark L. Hull, another great systematic thinker of the history of psychology, was also influenced by field theory, even though his behaviorist stand and his interest in learning theory did not seem to motivate the use of field theory. Hull devoted his entire career, starting around 1915, to elaborate a coherent learning theory. His last efforts were posthumously published yet unfinished. Hull, like Lewin, hoped to apply his theory to a wide range of behavioral phenomena. He was trying to apply Newton's method to psychology. Besides his indebtedness to Newton, Hull was profoundly influenced by Pavlov and Darwin. From our perspective, however, his gradual and irresistible shift toward Lewin's field theory is even more important.

In developing his learning theory, Hull's starting point was Pavlov. Reinforcement was and remained Hull's central concept through his long career. To elaborate an understanding of behavior in relation to objects in space, he argued that behavior has definite characteristics. He distinguished two different kinds of behavior and objects. Approach behavior is called *adience* and withdrawal behavior is called *abience*. Similarly, the object approached is called *adient object* and the object from which withdrawal occurs is called the *abient object*. The specific question about the perception of these objects was answered by the concept of stimulus intensity. Hull was trying to generalize these behaviors. According to Hull

Locomotion is highly generalized form of behavior, since walking as such to one point in space does not differ from walking to any other point in space. . . . An object whose stimuli have been conditioned to a reaction at one distance will end to evoke the reaction at any distance from which the stimuli may be received. (Hull, 1952/1964, p. 218)

As he was trying to extend his theory to rat maze learning, he needed a hypothetical concept, the *goal gradient*. According to this hypothesis, learning will be increasingly effective as the animal gets closer to the goal (e.g., the rat speeds up). This goal gradient concept has all the earmarks of a field concept: the gradient effect emanates from a source, the goal, and acts continuously over distance. The potential difference over the gradient acts like a force, accelerating the rat.

In his last work (Hull, 1952/1964), *A Behavior System*, Hull recognized the need for explaining anticipatory behavior. He went so far that in addition to using Lewin's field theory, he even used some of Tolman's concepts (e.g., expectation). Hull's intention was to extend his theory into problem solving as well as to the problem of values. He was also trying to argue that the theory of value can become a bona fide project within natural science rather than remaining a special territory of speculative philosophy.

## FIELD THEORIES IN GIBSON'S PSYCHOLOGY

### The Field of Safe Travel (Gibson & Crooks, 1938/1982)

Kurt Lewin had a profound influence on Gibson's intellectual development. One of Gibson's earliest writings (Gibson and Crooks, 1938/1982) reflecting this influence is his field theoretical analysis of automobile driving. Although this early article transcends Lewin's (1938) path analysis technique, it does not include Gibson's later conceptualization of the organism–environment interaction as an optic flow field. In 1938, Gibson had not yet developed fully his conceptual repertoire (e.g., perceptual system, optic flow field, affordance, invariants). For instance, in Gibson and Crooks' analysis of the automobile driving problem, the environment is represented as a visual field. Additional field concepts (e.g., the field of safe travel and minimal stopping zone) are defined as being nested within the visual field. The definitions of these fields are clear and almost self-sufficient.

A *visual field* is the visible surfaces of the environment that can be observed from a particular vantage point. Later, (1979/1986) Gibson called this a *vista*.<sup>1</sup>

A *field of safe travel* was defined as follows:

Within the boundaries of the road lies, according to our hypothesis, an indefinitely bounded field which we will name the field of safe travel. It consists, at any given moment, of the field of possible paths which the car may take unimpeded. Phenomenally it is a sort of tongue protruding forward along the road. Its boundaries are chiefly determined by objects or features of the terrain with a negative valence in perception—in other words obstacles. The field of safe travel itself has a positive valence, more especially along its mid-line. By valences, positive or negative, we refer to the meanings of objects by virtue of which we move toward some of them and away from others. . . . It is not, however, merely a subjective experience of the driver. It exists objectively as the actual field within which the car can safely operate, whether or not the driver is aware

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<sup>1</sup>The concept of *vista* is not identical to the colloquial use of the concept, which assumes possible rotation of the body and looking around. Gibson used the concept of *vista* to indicate the visible environment without the rotation of head or body. A *vista*, then, is the unoccluded portion of the environment visible through an opening, bounded by a doorway or the bony orbs of the eyes. *Vistas* are, therefore, restricted to the field of view. For a creature with protruding, lateralized eyes, peripheral vision is virtually unrestricted and the *vista* very nearly panoramic.

of it. It shifts and changes continually, bending and twisting with the road, and also elongating and contracting, widening and narrowing, according as obstacles encroach on it and limits its boundaries. (pp. 120–121)

A *field of minimum stopping zone* was defined as follows:

There is within the field of safe travel another zone, phenomenally less precise but behaviorally and objectively just as real, which is set by the minimum braking distance required to stop the car. It is the zone within which our driver could stop if he had to, and it can be supposed to be present implicitly in every driver's field. ... Unlike the field of safe travel, the size of the minimum stopping zone is dependent on the speed of the car—and also, it may be noted, on the conditions of road surface and of the brakes. ... The driver's awareness of how fast he is going does not consist of any estimate in miles per hour, instead, he is aware, among other things, of this distance within which he could stop. (p. 123)

These definitions, together with Figure 4, provide considerable insight into Gibson's early intuitions. One aspect of Gibson and Crooks's (1938/1982) description of the field of safe travel is particularly relevant for our purposes: "For the experienced driver, the car is in a sense projected to its potential location at the front of this zone" (p. 123). This approach contains several ingenious ideas. For instance, the subject–object dichotomy, residually present in the Gestalt approach, was cast in a new perspective, one in which the subject was replaced by two fields, the field of safe travel and the minimum stopping zone. However, this conceptualization, too, has some shortcomings. For instance, the environment has no well-articulated formal field description; Gibson used the term *visual field* without any specific func-

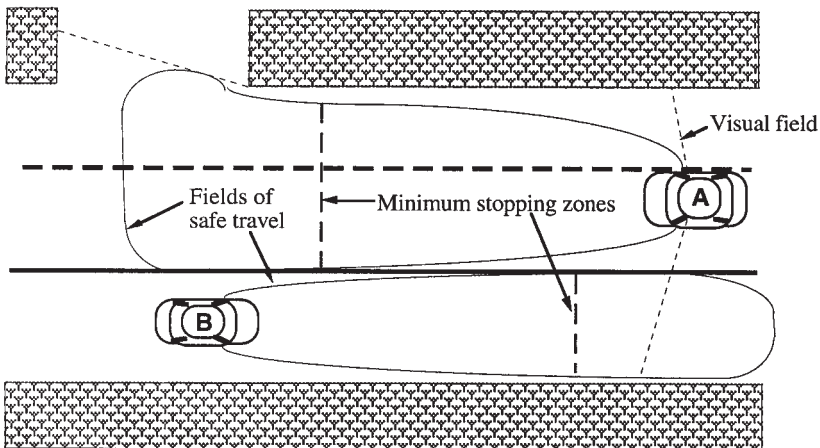


FIGURE 4 A depiction of Gibson and Crooks' (1938/1982) field theoretical analysis of car driving.

tional and perceptual connotation. Also, this approach lacks conceptual exactness (i.e., a formally clear interpretation of the analytic details).

In 1938, Gibson had not yet developed his radical theory of perception to explain how drivers can see in advance new opportunities by detecting information for action (prospective control).

### Discovery of the Optic Flow Field

Gibson (1979/1986, pp. 239–240) always considered himself an act psychologist in the spirit of Brentano but without the mentalism. However, for the scientific community, he was a perceptual psychologist. The key to understanding Gibson is to realize that these are not contradictory facts. Gibson was most interested in the perceptual support of the real-life activities of humans and animals. His paradigmatic problem was the perceptual control of action and, most fundamentally, how an organism can get around in a given environment. Although he was interested in all perceptual modalities (Gibson, 1966), his main interest centered on the problem of visual perception, in particular, the visual control of locomotion.

As a young scientist, Gibson recognized relatively early that laboratory experiments with impoverished stimuli have limited value for explaining real perceptual processes. Also, the inadequate conceptual repertoire of traditional perceptual theories forced him to reconsider fundamental issues. In Gestalt approaches, the perceptual theory was constructed from an abstract physical space (e.g., Euclidean, Riemannian, or perspective geometry). For example, depth cues were grounded in the relative position and size of objects, or certain properties of the geometry of space were considered the basis for distance perception. Clearly, these concepts were unsatisfactory for the young Gibson, who began to work on the problem of how actors estimate their direction of motion and relative position with respect to a given environment (e.g., terrestrial locomotion, aircraft landing). This line of research was supported by historical circumstances.

Gibson was involved in the training of pilots during World War II (Gibson, 1947). While working to identify the cues used by pilots in landing planes, he discovered the importance of optically specified surfaces, texture gradients, and optic flow. These were key insights by which to elaborate a radically new field theoretical description of the environment (Gibson, 1950), what he later called *ecological optics* (Gibson, 1960, 1961). One may speculate that this research helped to develop the basic concepts of ecological optics because fast rectilinear motion of an aircraft enhances the relative displacement of the points of environmental surfaces in the visual field. The rectilinear motion of an observer gives rise to a systematic global change in the projected images of surface points. The relative displacements of surface points can be represented by vectors. Under this view the visual field becomes a vector field.

One can notice the similarity between electromagnetic induction and the visual effect of a moving observer. In both cases, motion gives rise to a new field: an electric

current induces a magnetic field, and motion of an observer induces a velocity field, the *optic flow field*. Initially, Gibson focused on an environmental description as the basis for revising the theory of vision. In the forties and early fifties, Gibson introduced new additional concepts (e.g., optic flow, surface texture) but continued to use the traditional retinal image-based conception of vision. In other words, his flow-based theory of perception was conceived as perception of retinal image-flow.

### Later Developments on Optic Flow Field Theory

Gibson's (1966) second book revised the optic flow theory of perception and proposed that the optic flow field exists for a moving organism independently of eye-head movement. He argued that vision is a dynamic activity of the organism rather than mere neural processing of the complex stimuli of retinal surface. In his last book (Gibson 1979/1986), he summarized this new approach by saying that "natural vision depends on the eyes in the head on a body supported by the ground, the brain being only the central organ of a complete visual system" (p. 1). In addition, Gibson revised the theories of other perceptual modalities on the basis of the very same principles.

Having developed the idea of perceptual system, Gibson recognized the need for a more abstract level of description for the underlying processes in human perception. His concept of *affordance* was introduced to serve this purpose. Affordances are opportunities for action that the environment offers to a properly attuned organism. He went on to argue that optic flow includes all available information about the visible surface layout of the environment, including the functionalities it affords actors (i. e., opportunities for actions). Nevertheless, this radical theory of perceptual systems caused problems for Gibson's optic flow field theory as well. The optic flow field, which has a relatively simple structure during rectilinear motion, was soon recognized as problematic (Cutting 1986; Cutting, Springer, Braren, & Johnson, 1992; Kim & Turvey, 1994). How can a moving observer perceive the environmental layout if head turning and eye turning introduce additional transformations in the global optic flow? Gibson (1966) suggested that the "permanence in change, or in mathematical terms, the invariance under transformation" (p. 262) is the information equivalent to the information available to a moving observer without head and eye movement.

Does the visual system do vector field decomposition to filter out eye and head movement from the complex optic flow field? It became clear that postulating a nonretinal based optic flow was not sufficient to eliminate all problems.

Because Gibson's optic flow field is a vector field, it drew attention to the importance of tensors and tensor invariants in vision. Tensors can describe both global and local properties of the optic flow fields. For example, Koenderink (1986) showed how the differential invariants (described by tensors) that correspond to the transformations of optic flow provide a source of information for certain

functionalities (e.g., perception of direction of motion, rotation of motion). Global changes are informative about self-motion of the actor, whereas local transformations are related to the movement of objects or other organisms in the environment. For example, global expansion of the optic flow field, as viewed from an actor's perspective, corresponds to forward motion of that actor. Conversely, global contraction of the optic flow indicates backward motion of the actor. If motion is also rectilinear, then the center of expansion (contraction) specifies the direction of motion. Similarly, for objects (organisms) moving in the visual field of an actor, the corresponding local changes in the optic flow will have a local expansion if the object is approaching the observer and a local contraction if the object (organism) is moving away from the actor.

These properties of optic flow were explored in detail, frequently in the context of image analysis. Optic flow analysis and image analysis under dynamic conditions have a common denominator, namely retinal image flow, which was the early interpretation of Gibson's optic flow (ignoring the eye movement). Tensor analysis was a successful technique in both approaches; however, generalizing these elementary tensor components to a complex scenario proved problematic (Koenderink, 1990, 1992). For example, understanding the use of optic flow as information about locomotion in the case of curvilinear motion faces major challenges (Kim & Turvey, 1994; Wertheim, 1994).

Although, formally, an optic flow field of a curvilinear motion can be decomposed into the sum of its translational and rotational components, the validity of applying similar decomposition methods to the actor's visual process can be and has been strongly debated. W. H. Warren and Hannon (1988), for example, have argued that curvilinear motion can be characterized by the radius of curvature of a path and that this information is both available and used by the actor. Kim and Turvey (1994) pointed out, however, that the radius estimation is also problematic and suggested a different approach borrowed from fluid mechanics. They recognized that optic flow is a vector field generated by the infinitesimal vector displacement of a moving observer, and as such, it cannot provide global information on path formation (selection) during curve negotiation. They argued that optic flow trajectories generated by the relative displacement of the surface points of the environment layout are used as information for curve negotiation.

In sum, Gibson's notion of perceptual system and the analysis of nonrectilinear motion revealed a few problems with optic flow field theory. Although Gibson suggested that his theory should be elevated to a more abstract level, formal generalization of the optic flow field theory remained an unresolved issue.

### RECENT DEVELOPMENTS IN ECOLOGICAL PSYCHOLOGY

Our overview of Gibson's field theoretical efforts revealed that his attempts (Gibson 1950, 1966, 1979/1986; Gibson & Crooks, 1938/1982) to capture organism-

environment interaction used interaction fields. Despite this fundamental similarity, there are significant differences between his early approach (Gibson & Crooks, 1938/1982) and his latest view (Gibson, 1979/1986). The field of safe travel was based on possible action trajectories and implied that drivers are able to perceive this field. Later, Gibson realized that traditional approaches to visual perception are inadequate for capturing these and other essential features of visual control of locomotion. Gibson's optic flow theory provided a radically new approach for tackling these issues. In this framework, perception and locomotion are tightly linked: ego-motion generates a global flow field and a flow field creates the impression of ego-motion. Nevertheless, the optic flow field has proved insufficient to explain how drivers control their field of safe travel by visual perception. For instance, current debates on the role of eye movement and the use of the optic flow field in curve negotiation are centered around this problem.

### **Current Status of Optic Flow Field Theory**

Over the ensuing decades, the optic flow field description has provided a powerful and popular tool to address a number of diverse problems in visual perception as it pertains to the control of action (R. Warren & Wertheim, 1990). In appraising the state of development of optic flow field theory, a respected expert recently concluded that although the mathematical side is quite well established in principle, it cannot be considered a closed subject as yet because the kinds of solutions that are of most interest to psychology, namely, solutions to problems in visual perception, have hardly been considered at all (Koenderink, 1990). W. H. Warren's (1995, 1998) articles provide a useful overview of this unresolved issue.

However, how can one evaluate the state of the art in the use of optic flow without a proper theoretical framework for vision? How can one claim that the optic flow theory for visual perception is not fully developed? On what basis can R. Warren (R. Warren & Wertheim, 1990) argue that the application of optic flow field to the perceptual control of action (self-motion) is even less developed? Clearly, one needs at least a few guiding principles if one is to judge the level of development of the theory of the optic flow field and its application to research. The fundamental principles can be outlined by answering this question: What is the minimum requirement for addressing the fundamental role of visual perception?

Apparently, visual perception evolved as a means for helping the organism to locomote and find what is good and avoid what is harmful. This suggests a dual role for vision: guidance of locomotion and pattern recognition. Indeed, this distinction is used in most traditional approaches as well as several research projects motivated by Gibson. Within the Gibsonian framework, locomotion guidance is discussed in optic flow studies and the problem of recognition can be linked to the properties of the environmental layout. Both aspects of vision, however, are controversial. Some of the problems with optic flow theory (e.g., role of eye, head, and body movement)

have already been mentioned and are further discussed later. Perception of surface layout is also problematic because researchers often take Gibson's (1950) early view as a starting point and follow an image processing theoretical line.

It has been shown in several research projects (Flascher, Kadar, Garrett, Meyer, & Shaw, 1995; Frey, 1995; Wann, Rushton, & Lee, 1995; W. H. Warren, Kay, & Yilmaz, 1996) that the minimum requirement for a theory of visual perception is that perception has to be tightly coupled to action. Furthermore, this relation should be flexible enough to handle a variety of situations and a number of task constraints. Under natural circumstances, an organism is usually engaged in one or more actions. Actions generally take the form of goal-directed behavior. Consequently, understanding goal-directed behavior should be the primary focus of any theory.

Along this line of thought, it has been argued that intentionality plays a crucial role in perceptual and action processes (Heft, 1989; Reed, 1993; Shaw, Kadar, & Kinsella-Shaw, 1994; Shaw & Kinsella-Shaw, 1988; Shaw, Kugler, & Kinsella-Shaw, 1990). Traditionally, it was believed that intention (or motivation) directs attention in perception and that attention was similar to a spotlight that illuminates the important parts of the visual field (Eriksen & Hoffman, 1972); alternatively, attention was conceived as a filter that lets the relevant information go through while blocking the irrelevant (Broadbent, 1958). Recognizing the close relation between action and perception has led many scientists to think about intentionality in a different fashion.

Gibson (1979/1986) himself used intentionality implicitly in discussing the "rules for visual control of locomotion" (p. 232). Several researchers (Heft, 1989; Kadar & Effken, 1994; Reed, 1993; Turvey, 1992) emphasized the need for making intentionality explicit. There are several attempts to use mathematical formalism to capture fundamental features of intentionality. For example, it has been suggested (Kugler & Turvey, 1987; Shaw & Kinsella-Shaw, 1988) that intention in a successful goal-directed behavior can be viewed as an operator that couples the perceptual and the action systems and provides global task constraints.<sup>2</sup> These ideas may provide a minimal context for evaluating existing approaches to the use of optic flow field and other field theories in ecological psychology.

### **Recent Field Theoretical Efforts in Ecological Psychology**

In his early career, Gibson introduced new concepts to help analyze the problems of visual perception from a functionalist perspective. That is, he reformulated, with reasonable success, the ingredients that must be contained in perceptual information as required to support the natural activities of animals. Although Gibson devel-

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<sup>2</sup>In addition, it has been mathematically shown that such a coupling of information and control exhibits an action constancy (inner product invariant of information detected and control applied) whenever the path followed is a successful goal path (Shaw, Kadar, Sim, & Repperger, 1992).

oped these novel ideas over many years, he never lost sight of his major objective, namely, to understand perception as a basis for action. In this new approach, the optic flow field played a key role as various successful applications have already shown.

In an interesting application, Michael Benedikt (1979), an architect, developed a measurement technique using Gibson's idea of vista, the visual expanse revealed by moving from one place to another. Benedikt (1979; S. L. Davis & Benedikt, 1979) showed how (locomotory) transitions between vistas can be formally characterized as a smooth path with a specific information measure associated with each point on the path (Figure 5). The information measure of the surrounding, optically specified environment yields an omnidirectional isosimilarity contour, whose directional values (perspectives) are called *isovists*. For example, an isovist measure, say for occlusivity, is a measure of the ratio of visible surface area to total surface area. Such measures have practical application to the design of the layout of architectural environments and, in many cases, offer an objective measure of affordance properties (e.g., one's privacy versus one's public exposure).

A transition from one vista to another defines a path integral. Thus, movements by an actor are likely to alter the integral of isovist measures, such as occlusivity, because some surface areas, previously occluded, may become disoccluded whereas others, not previously occluded, may become occluded. A difference in isovist measures over the path integral would correspond to the effects wrought by the intentional control of locomotion. Unfortunately, Benedikt did not pursue this line of thought, leaving the problem of path formation implicit.

Benedikt's theory highlights the fact that among the variety of concerns with the optic flow theory, the relation between perception and action in an intentional context is especially crucial. Most researchers agree that Gibson's radical theory of perceptual systems undermined the traditional distinction between sensation and perception. However, there seems to be a disagreement about whether it is possible

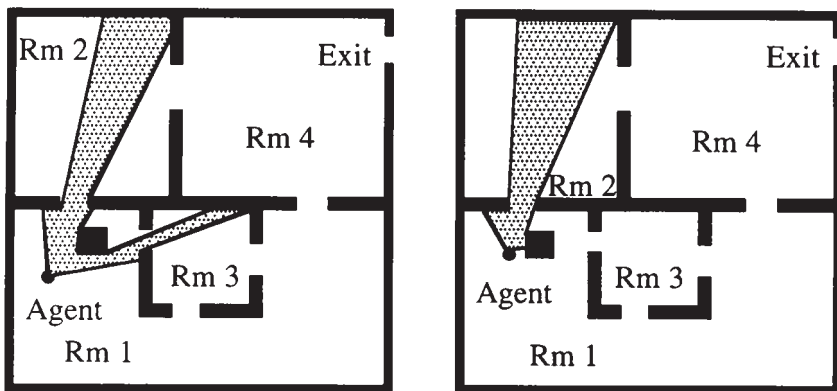


FIGURE 5 Illustration of the changing vistas as an actor is moving from Room 1 to Room 2. The changing vistas provide the basis for Benedikt's concept of isovist field.

to maintain the perception versus action distinction. Clearly, within the Gibsonian framework of perceptual systems a coherent distinction between perception and action cannot be based on the traditional sensory versus motor distinction. It is less obvious, however, how to find an even-handed treatment of perception and action. Various recent field theoretical approaches are trying to resolve this issue.

One attempt to align action and perception was made by Shaw and his colleagues (Shaw & Turvey, 1981; Shaw, Turvey, & Mace, 1982) in the following way. An affordance (e.g., edible food) is an opportunity for an action to be realized if the affordance is selected as an intended goal (e.g., to eat the food) and if there is information specifying its location and a path to it is allowed. This conditional definition of an affordance shows it to be dispositional, that is, a real property of the environment whose realization as a goal is merely potential until certain instrumental means are provided the actor. These means for realizing an affordance goal involve two instrumental acts (consistent with the fact that Gibson was an act psychologist): first, detecting the available goal-specific information and, second, applying the appropriate goal-relevant controls so as to navigate a path to the goal in accordance with the affordance information. This goal-path-informed control has been termed the *effectivity* that fits the affordance in question.

Where the affordance concept refers to real properties of the environment taken in reference to potential properties of the organism (i.e., its abilities), an effectivity does not merely refer to the opportunity (potential) for an action but to the actual acts involved in realizing the stipulated action. Hence there is an affordance–effectivity fit whenever a successful goal-directed action is produced. The fit is not between two potentials but between a potential and the process realizing that potential; it is, in Aristotelian terms, the difference between potentiation and actualization. This fit is not between equals but between promise and performance. To miss this point is to leave affordances as conditions for actions that have no way to be realized. Affordance and effectivity refer the environmental information to the organism's control and vice-versa and hence complement each other. They also set reciprocal boundary conditions on each other vis-à-vis the goal path they share. There are field implications of this path approach that are dealt with later.

By contrast to this even-handed treatment of action and perception, Reed (1982) proposed treating action as being more fundamental than perception. He made several attempts to sort out the taxonomy of action systems. In his 1982 article, he listed eight different action systems. Later, Reed (1993) suggested that we split the affordance realization activity into two different processes: exploratory activity is for “detection and use of information about affordances” and performatory activity in which “some affordances of the environment (and this includes social environment) is altered” (p. 66). In his last version of this taxonomy, Reed (1996) further distinguished between social and nonsocial performatory actions, suggesting that he wanted to deal with social interaction separately.

These ideas are based on actual action but Reed wanted to link them to potentially available actions as well. Reed attempted to generalize Gibson and Crooks'

(1938/1982) action field ideas and to link to other action field concepts including Valsiner's and Vygotsky's views. To generalize his action theory to action fields, Reed borrowed two intuitive field concepts from Valsiner (1987) to distinguish between the field of promoted action and the field of free action:

*Field of promoted action (FPA):* Those objects, places, events, and their affordances, which an individual is encouraged to realize. These persistent and invariant patterns of encouragement are hypothesized to exist for individuals, families, and other cultural groupings.

*Field of free action (FFA):* Those objects, places, events, and their affordances, that an individual can realize on his or her own and that the individual is allowed to use. This field expands and contracts reciprocally to the field of promoted action.

Reed used these distinctions to define Vygotsky's (1986) zone of proximal (potential) development for any given skill as the difference between the FPA and the FFA. This represents the range of affordances and the variety of contexts within which social scaffolding facilitates affordance usage.

The striking similarity between these fields (FPA and FFA) and Gibson and Crooks' notion of field of safe travel is transparent. Reed's conceptualization is also generic but heuristic, leaving it unclear how these concepts could be used in experimental verification. How are exploratory and performatory processes related?

Shaw and his colleagues (Kugler, Shaw, Vicente, & Kinsella-Shaw, 1990; Shaw et al., 1994; Shaw & Kinsella-Shaw, 1988) have also tried to resolve the problem of linking perception and action by using action as the fundamental concept. In trying to avoid ambiguity, they (Kugler et al., 1990; Shaw et al., 1994; Shaw & Kinsella-Shaw, 1988) focused on the mathematical formalization of a generalized action concept comprising both perception and action within an intentional context. The proposed theory is called *intentional dynamics* to emphasize the key role of intentionality as a global constraint on the field of possible actions. They used several mathematical formalisms (e.g., group theory, ordinary differential equations, integral equations, quantum mechanical methods) to describe fundamental aspects of successful goal-directed behavior. These formalisms are closely related, rather than independent, attempts to provide different perspectives on the same problem structure. Because Gibson used field theory, perhaps, field theory is the simplest technique to demonstrate how intentional dynamics attempts to clarify certain ambiguities and remedy some of the previously mentioned shortcomings in Gibson's theory. All of these attempts have one requirement in common, the need to treat goal-directed behavior under a lattice of mathematical dualities consisting of organism–environment, affordance–effectivity, perceiving–acting, and information–control. Together these dualities define a conditionally closed ecosystem—a coalition, or a structure closed under those conditions that make goal-directed behaviors successful (Shaw & Turvey, 1981; Turvey & Shaw, 1995).

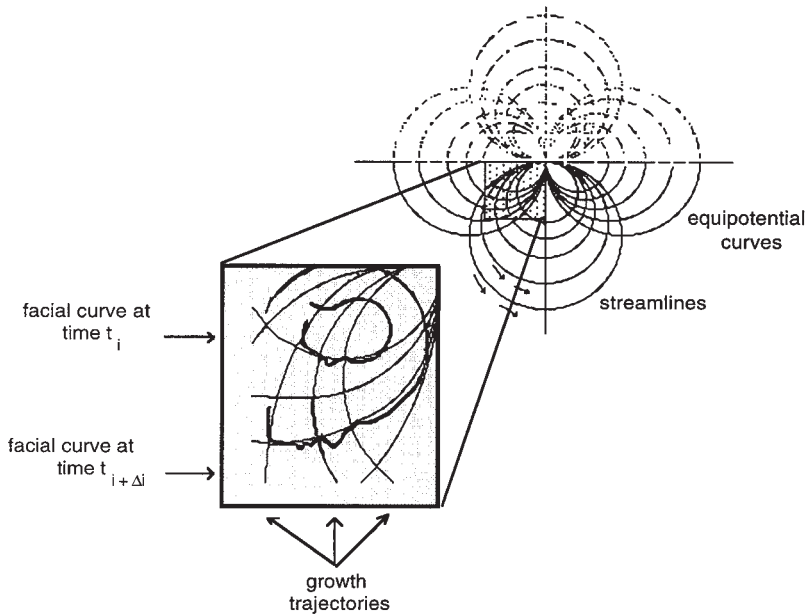


FIGURE 6 The tangent circle model of craniofacial growth. The growth trajectories are represented by streamlines orthogonal to the field of growth potential.

Gibson's early field theory (Gibson & Crooks, 1938/1982), as well as the optic flow field theory (Gibson, 1950, 1979/1986), describes organism–environment interactions, but both approaches have fundamental shortcomings. The field of safe travel describes the possible actions in an intentional context, although it keeps the visual information implicit; conversely, the optic flow field characterizes visual information, although it keeps the action (momentum changes over position) remained implicit. To remedy these shortcomings, Kadar, Flascher, and Shaw (1993, 1995) proposed a hydrodynamic flow field to integrate both goal-specific visual information (in the optic flow field) and the goal-relevant control (field of possible action flow). Formally, a potential flow field of an ideal fluid with constraints can be used to describe the orthogonal field of information and movement trajectories. A similar approach was previously used in an application to the treatment of craniofacial growth deformity (Mark, Shaw, & Pittenger, 1988; see Figure 6).<sup>3</sup>

<sup>3</sup>Shaw and his colleagues showed that information for age-level of faces obeys a growth transformation modeled as a streamline in a gravitational constrained, hydrodynamic field. Moreover, *deformed growth*, defined as departure from such streamlines, is readily perceived (Carello, Grososky, Shaw, Pittenger, & Mark, 1989) and thus can be used in treatment plans involving the tuning of growth directors (e.g., bands, braces) so as to control the application of forces to steer the patient along intended (normal growth) paths in growth space (Shaw, Mark, Jenkins, & Mingolla, 1982).

The two-dimensional fields of ideal fluid flow are best described by complex holomorphic functions (Milne-Thomson, 1968). These fields satisfy the Laplacian differential equation:

$$LV = \nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0 \quad (1)$$

where  $V = V(x, y)$  is a two-dimensional potential function. There exists two orthogonal sets of solution functions  $\psi(x, y)$  and  $\phi(x, y)$  of the Laplacian equation. The  $\psi(x, y)$  and  $\phi(x, y)$  functions are called the *stream* and *velocity potential* functions for the potential flow of ideal fluid. They satisfy the Cauchy–Riemann equations:

$$\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y} \quad \frac{\partial \psi}{\partial x} = -\frac{\partial \phi}{\partial y} \quad (2)$$

The  $w(x, y) = \phi(x, y) + i\psi(x, y)$  function is the complex potential of the fluid motion. This is a holomorphic function of the complex variable  $z = x + iy$  (see Figure 7). The real part is composed of the streamline functions that generate a field. These functions correspond to the field of possible movement trajectories. Kadar et al. (1995) called this field a *control field*.

The field of the imaginary part of the complex holomorphic map, called a *velocity potential*, is generated by contours that lie orthogonal to the field of streamlines (movement trajectories). The orthogonality of these lines to the streamlines (paths) reminds us that navigation in a flat 2D space is a gradient-based motion in a potential field. By analogy, we can interpret the velocity potential field as an information gradient field that drives (i.e., attracts) the navigator toward a goal. Practically, we may say that the navigator is maximizing the rate of change in distance when moving along a gradient in that field, that is, it goes as fast as it can in the direction of the information gradient (recall Hull's, 1952/1964, goal-gradient hypothesis).

This suggests a direct analogy between the navigational skill of lower order species and humans because information gradients are commonly used by various organisms, such as bacteria, termites, spiders, humans (Gladwin, 1964; Kadar, 1996; Koshland, 1980; Kugler & Turvey, 1987). This strategy is known as *taxis behavior*, an orienting movement pattern toward the direction of a gradient of a field (e.g., *geotaxis* toward the center of gravity, *chemotaxis* toward the source of chemical diffusion field, *phototaxis* toward light source). These orienting movements are usually considered as primitive behavior patterns of some lower order species. Kadar, however, recognized that these patterns are generic. They are the fundamental ele-

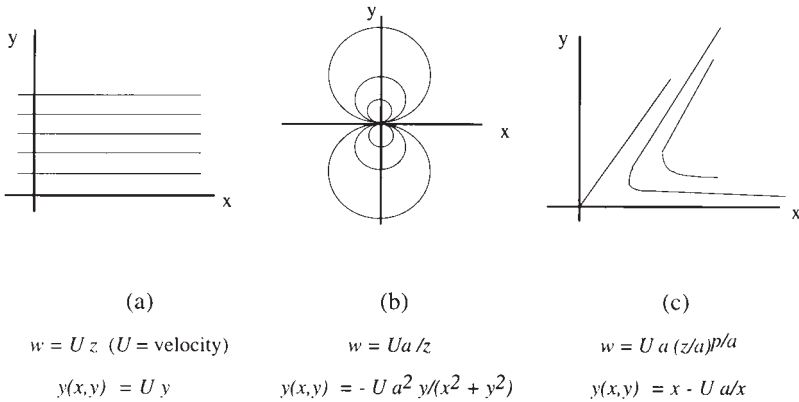


FIGURE 7 Examples of holomorphic functions. These functions illustrates three different mappings from  $z$  plane to  $w$  plane with parameters  $U$ ,  $p$ , and  $a$ . The depicted lines are the stream-line functions. The orthogonal set of functions, so-called velocity potentials, are not included in these figures.

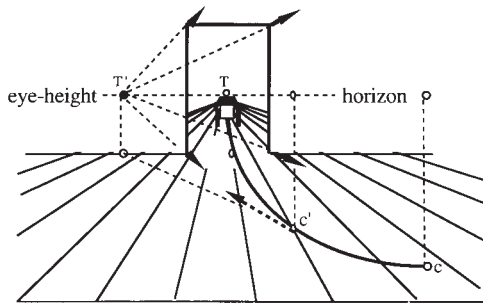
mentary units of locomotory behavior for all species ranging from bacteria to humans.<sup>4</sup>

Empirical data from time-to-contact studies can also be viewed as a support for the orthogonality of the information field (optic expansion) and movement trajectories in an intentional task context (Kadar, 1996; Lee, 1974, 1990). Kim and Turvey (1994), however, contested the usefulness of the optic flow expansion for anticipatory tasks, such as curve negotiation. Although they also used the technique of fluid flow field orthogonal decomposition, they argued that participants use optic flow trajectories to anticipate egomotion. Their argument was based on two research findings. W. H. Warren, Blackwell, Kurtz, Hatsopoulos, and Kalish (1991), using random dot displays to generate curvilinear optic flow, randomized the magnitude of each vector component of the flow fields while preserving the directional components. Participants were shown to be reliable in perception of heading. Using a similar display but generating elliptical trajectories, Kim and Turvey (1998) also found reliable performance in their experiments. These research findings, however, do not discard the possibility of using global optic expansion for controlling locomotion. In these experiments, the randomization was only local and the mean velocity field remained basically unchanged. Thus, in principle, the global vector field can still be used for detection of optic expansion that is stochastically regular in flow (Pittenger & King, 1973; Todd, 1985). Furthermore, participants may use the strategy suggested by Gibson

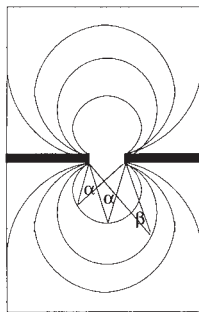
<sup>4</sup>To be more exact, with the use of the fluid flow model, Kadar (1996) showed that moving from one position (A) to another (B) can be viewed as fluid flow from source (A) to sink (B).

and Crooks (1938/1982); that is, they project themselves ahead and at the same time they are able to detect global optic flow expansion ahead of themselves. Gibson maintained this early view, as his last book (Gibson, 1979/1986) shows. In criticizing the traditional static perspective-based theories of vision, he argued for a dynamic globalist view of perception.

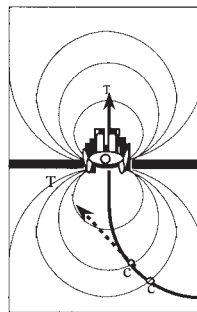
It is obvious that a motionless observer can see the world from a single point of observation and can thus notice the perspectives of things. It is not so obvious but it is true that an observer who is moving about sees the world at no point of observation and thus, strictly speaking, cannot notice the perspectives of things. The implications are radical. Seeing the world at a traveling point of observation, over a long enough time for sufficiently extended set of paths, begins to be perceiving the world at all points of observation, as if one could be everywhere at once. To be everywhere at once with nothing hidden is to be all-seeing, like God. (p. 197)



(a)



(b)



(c)

FIGURE 8 Passing through a doorway using an isoangular field. (a) Sideview of a passing-through task. (b) The isoangular field of a doorway consists of a set of circles. Each circle consists of points with one specific visual angle ( $\alpha$ ,  $\beta$ , etc.). (c) Top view of the gradient path of Figure 8a along an isovist field.

It is important to highlight two aspects of this approach. First, this radical view makes Gibson's theory clearly distinct from Hull's neobehaviorist use of field theory because he considered perception as nonlocal phenomenon in space–time. Second, the nonlocality of perceptual perspective should be conceived as valid only within a limited space-time domain defined by the functional context. Otherwise the nonlocality postulate may become absurd.

The nonlocal complex field approach can also be applied to Benedikt's isovist fields (Kadar et al., 1995). The dynamic information effects of the isovist field are due to the existence of control measures that are orthogonal (conjugate) to the isovist field (information) equations. Thus, the limitation in Benedikt's theory can be overcome, for the construction of the conjugate field of action paths can be achieved by standard techniques used in hydrodynamic flow. As a matter of fact, this approach is a generalization of the gradient strategy observed in spatial navigation of various species (Kadar, 1996).

In sum, the orthogonal fields describe what a person sees (using functionally specific information from the optic flow) as a function of what a person does (control of ego-motion) moving along a given trajectory. The family of streamline functions can be viewed as a control field. The set of orthogonal functions, viewed as the velocity potential field, generates an information field (see Figure 8).

These developments in field theoretical approaches to organism–environment interaction have highlighted the significance of mathematical field theory. The technical issues encountered, however, have become topics of major interest in other disciplines. For example, the problem of prospective control is a crucial issue being addressed in robot navigation. Because artificial intelligence (AI) research projects, usually, have huge resources (financial, mathematical, as well as technical) for addressing agent–environment interaction, it is instructive to review briefly some of the recent developments in this area.

## DEVELOPMENTS IN AI

Because traditional representational approaches have failed to deliver robust and flexible real-time solutions, researchers into the problem of autonomous navigation are eager to try new ideas. As a result, various kinds of field theories are on the top of the list of candidate alternative strategies. These developments often lead to the reappearance of old ideas in more refined forms. For instance, Lewin's (1936) ambitious project seems to resurface in the following project, which took advantage of efficient data collecting features of a computer interface.

### **A Generic Process Approach to Human–Environment Interaction (Kirlik, Miller & Jagacinski, 1993)**

Kirlik et al. (1993) elaborated a highly complex model of a computer-mediated, skilled human–environment interaction in an uncertain environment. The empiri-

cal part of the research was based on a simulation of a combined supervisory and manual control task. Crews of a simulated cockpit controlled their scout craft either manually or by autopilot. In addition, crews had supervisory control over four semi-autonomous craft that could be used to help their performance. Two graphic displays were used to provide a top view of the irregularly forested environment and a dynamic forward-looking view (pilot view). Crews had to locate and process valued objects with efficient use of their resources.

Fundamental to their model is the aim to understand human activity as skilled behavior constrained by environmental and psychological factors. The external environment is represented as a dynamically changing set of opportunities for action (searching, locomoting, loading, refueling, etc.). More specifically, Kirlik et al. (1993) argued that their model uses affordance-based environmental representation, which is objective, that is, independent of the psychological processes by which these properties are detected and used to guide behavior. The second major component is a representation of skillful human cognitive processes that include dynamic decision making and planning.

Although this model has several remarkable features, it has a strong resemblance to Lewin's theory. In Lewin's model the environment is represented by action paths. Kirlik et al.'s (1993) model differed from Lewin's in that the environment is represented by affordance distributions, which have been calculated by simple procedures. In both models, however, the psychology of perception remains implicit. Kirlik et al. admitted that they were unable "to specify adequately and exhaustively the information available from the graphical displays ... [and] the psychological description of how the crew may have detected the affordances using the interface information is incomplete." (p. 936). They did not explicitly mention the concept of field but their model can still be interpreted as being implicitly a field-based approach. The main problem with this approach, however, is that the computer interface provides an external observer perspective that can cognitively dominate the dynamically involved actor's perspective. Although in Lewin's method a post hoc analysis can keep perceptual factors implicit, in this model the top view (bird's eye view) can render the perceptual skill of a dynamically involved actor secondary. This was one of the reasons why Gibson shifted the focus of his research to the perceptual aspect of controlling locomotion.

### **Perceptual Control of Locomotion**

In pursuing pioneering research on the theory of optic flow, the traditional problems of perception theories (e.g., object perception and abstract space perception) became irrelevant and anachronistic. Although many researchers in AI are still pursuing these traditional projects, the development of computational theory cannot be ignored, in part, because the cognitive computational approach has slowly picked up on the potential usefulness of several of Gibson's ideas. Also, during the last cou-

ple of decades, there has been an enormous intellectual effort invested in developing sophisticated, efficient, formal techniques, some of which may be useful in a variety of different paradigms, such as pattern recognition, object recognition, and space perception.

In the cognitivist paradigm, vision is considered to be a movie-like process, that is, a complex sequence of static (retinal) images. This approach requires two types of analysis: the processing of retinal images and comparing the differences between consecutive retinal images. Depending on the theoretical perspective one takes, image processing analyses can be construed in different ways. In the early research in artificial vision, for instance, scene analysis traditionally used cues (e.g., Guzman, 1968). Motivated by neurophysiological findings, Marr (1982) introduced the Fourier filter technique for image processing. Gibson's (1950) early theory of visual perception, in which optic flow was equated to retinal flow, can also be used in this theoretical framework (Waxman & Ullman, 1985). Although the use of optic flow in AI is usually based on image transformations, certain theoretical results can be borrowed. Formally, image transformations can also be viewed as a quantized optic flow field. Consequently, any powerful method can potentially be adapted to an optic flow analysis. For this reason, it is useful to consider current trends in computational vision.

### **New Methods for an Abstract Field Description of the Optic (or Image) Flow Field**

The differential geometric approach succeeded by using elementary tensor components to characterize certain simple global or local properties of the optic flow. However, if we try to use the same technique in a more complex environment, we face the following problem. If a cluttered environment has objects that are moving relative to each other and relative to the observer, what kind of integration would be needed to process the available information—even for simple tasks, such as being able to get around the environment without collisions? It appears that some kind of higher order processing will be needed. The most straightforward technique for this integrative process is multilevel, hierarchical grouping of information components. This direct and rather tempting route has been used by many (Grossberg & Mingolla, 1985; Marr, 1982). However, in different research paradigms, the elementary components are quite different. For instance, in the 1970s, cue theory was popular (Winston, 1975), whereas in the 1980s, after Marr's work (1982), Fourier decomposition was more commonly used.

The hierarchical strategy, however, has several major shortcomings. It has high computational complexity, relies on too much intelligence borrowed from an external agency, and can be constructed for specific scenarios but not for generic use because it cannot use intrinsic, self-organizing principles to accommodate the processing systems to new situations. Regarding the optic flow field-based, differential

geometric approach, it seems plausible that higher order processing would require some other technique than tensor analysis. These various problems suggest that the biophysiological (ecological) validity of this kind of hierarchical processing system is questionable, leading several researchers to look for new techniques. Next, consider a brief outline of a promising new approach to optic flow field processing.

Grouping (integrating) information can be done in a more direct fashion, which, at the same time, preserves the fundamental tensor analysis technique (Granlund, 1978; Wilson & Knutsson, 1988). Consider an abstract, higher dimensional space consisting of the coupling of two spaces, a base space called the *image space* in which objects (patterns, events) are to be recognized and the other, an ancillary *parameter space* in which the object of interest can be reparameterized in ways to aid in the task of recognition. Although, increasing the dimensionality of the so-called image space can make it less tractable or even problematic for processing (computational) requirements, the parameter space can often be designed to express global properties of the object quite elegantly.<sup>5</sup> By mapping the high dimensional image space into the parameter space, a complex global information detection problem in standard visual space can be converted into a simpler local problem in the parameter (information) space. The less tractable problem of recognizing complex patterns with global properties can be transformed into a more tractable problem of recognizing simpler patterns of local features. The Hough transform (a special case of the older, better known Radon transform) is the most commonly used technique to accomplish this (Hough, 1962; Illingworth & Kittler, 1988).

Traditionally, this method was used for feature-based scene analysis. For instance, in edge analysis, line segments are mapped into clusters, that is, colinear segments are mapped into points close to each other. By using time as an additional dimension in the base space, the line segments will be optic flow vectors (displacements), and the traditional edge analysis can be used for processing tensor properties in the differential geometric approach. Because the original Hough transform has an unbounded parameter space and contains singularities, several modifications have been suggested (E. R. Davis, 1986; Duda & Hart, 1972; Granlund, 1978). The most promising is the so-called Möbius strip mapping (Westin & Knutsson, 1994), which has several topological advantages (e.g., the parameter space is bounded, singularities are avoided, and the mapping is one to one).

The availability of the Hough transform and similar new techniques encouraged several groups of scientists and engineers to expand the field of computational vision and robotics in new directions. For instance, this technique was one of the novelties of a major project conducted in the early nineties. Because this project has several progressive ideas which anticipate the future trends in research, it is discussed next.

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<sup>5</sup>This parameter space is defined by projection operators. This suggests that quantum mechanical formalism may be a proper technique to describing visual perceptual processes because it too can be based on projection operators but in Hilbert space rather than Euclidean space.

### **The Vision as Process (VAP) Project**

During the late 1980s, there was an increased interest in the use of the active control of vision in scene analysis. What motivated this change in focus? Although scene analysis was still regarded as image processing, it was recognized that it is futile to try to obtain all the information from an image (Bajcsy, 1988). Researchers turned their attention to natural perceptual systems. In biological perception, an organism is not a detached observer of the world but rather an active participant whose perception is usually constrained by goal-directed behavior. This implies that it is not necessary to provide a complete processing of the perceptual world. Instead, the focus should be on the relevant information needed for user-defined tasks (Jensen, Nielsen, & Christensen, 1990; Tsotsos, 1987).

If vision exists to support the purposeful behavior of an active organism, engineers must face the same problem as Gibson and his followers. The challenge for engineers is to come up with real-time computation processes. The challenge for ecological psychologists is to come up with an information description and information detection process that is psychologically sound. Researchers in computer vision realized that new methods are needed primarily in two problem areas: (a) The informational model of the environment requires new, qualitatively different descriptors, and (b) a solution to how the attention of the continuously moving system may be controlled.

In 1989, the European Commission funded a consortium of six laboratories to start a thorough investigation of the visual system as a continuously operating controlled system. In 1992, the first test-bed system was ready to operate in real time. Two innovative ideas emerged from this effort: control of the fixation of the robotic stereo camera and the development and successful implementation of a new version of the Hough transform, the Möbius parameterization.

This line of thinking is quite close to the ecological approach to perception with one crucial difference. Although in the VAP project, vision is controlled, in the ecological approach the role of perception is to control action. To be more precise, in the ecological perspective perceptual control implies mutual control between perception and action. Unfortunately, the VAP project fails to address this reciprocal and mutual relation between information and control. This shortcoming is closely related to another problem. In the VAP project, the issue of identifying relevant information was solved by constraining (or limiting) the visual field. Instead of asking the question, "What is the task relevant information?," it was assumed that goal-specific information is local and can be found in the visual field in the neighborhood of the goal.

### **New Directions in Robotics**

Currently, experimentation with new techniques is being conducted by several investigators of robotic systems. In the mobile robotics literature, there is a trend of

looking for new ideas in biology and psychology. Researchers recognized that simple movement control, including locomotion, should be understood without relying on sophisticated and very complex internal cognitive processes. In an effort to find natural solutions, scientists are trying to understand and mimic simple organisms. Clearly, insects are the most popular creatures these days, but some researchers (Kadar & Virk, 1998) have argued that even the insects are too complex to start with.

With the increase of interest in lower order species, researchers in robotics became interested in behaviorism. In particular, Hull's gradient approach gained popularity, because in robot navigation goal finding and obstacle avoidance are fundamental but unresolved problems. Using the gradient (potential) field seems to be a promising strategy for addressing these problems in a simple fashion. Arbib and House (1987) used this method to model prey behavior. The prey sets up a concentric attractant field whose strength decays with distance from itself. Barriers are also represented by more localized fields (repellent or abient) than that of the prey. Together with these fields a toad's urge to move is also represented with a radially diverging field. The actual path of the animal (toad) is then determined by the interaction of these fields. To put it differently, the various fields exert various forces on the organism. The target exerts an attractive force, obstacles provide repulsive forces, and the resultant sum of these forces determines the path (sum of local speed and direction) of the navigator.

There are several applications of this approach in robotics. Arkin (1989), for instance, used this method for a path-planning model. R. Warren (1990) applied a similar technique for coordinated path planning of multiple robots in an environment cluttered with obstacles. This model was successful in explaining detour behavior with a simple barrier (see Figure 9). Payton (1990) described this technique as a representational method for action resources. This modeling strategy, however, can be too complex if linked to a representational approach.

In both the VAP project and the application of potential field technique, traditional representational methods were used. By contrast, another group of researchers tried to eliminate the representational approach. They recognized that the representational approach to describing the environment is not particularly helpful (Beer, 1990; Brooks, 1991; Connell, 1987, 1990; Kirsh, 1991). Quite to the contrary, representation unnecessarily increases the complexity of the problem and the computational load. In robotics, the computational load is especially crucial because the control of movement involves very many degrees of freedom and, therefore, makes heavy computational demands. If the environmental description is not efficient, real-time processing is impossible, even with very powerful microprocessors. As a result, the representational technique was eliminated, and the world was used as its own representation.

Despite important progress in this new direction until recently, the functional connection between environment and robot remains artificial. The unnatural character of the relation between the robot and the environment can be seen

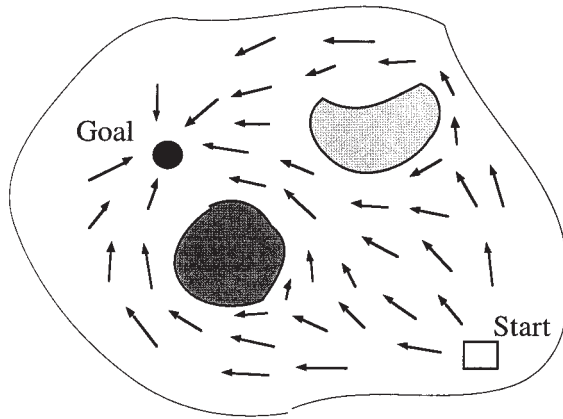


FIGURE 9 Illustration of the gradient field by gradient vectors. The gradient vectors can be constructed by the representation of the environment and the movement trajectories can be generated by vector integration.

clearly in the shape of movement trajectories. Typically, trajectories either follow a wall at a distance or are created artificially by imposing unnatural, extrinsic, geometric constraints. Also, representational approaches are often used in connection with promising field theoretical applications. A principled solution would require that such problems be resolved by constraints that arise naturally from the mutual interaction of the agent (e.g., robot) with its environment, as a function of a field imposed by the intentional task as suggested by intentional dynamics theory (Effken & Shaw, 1992). Kadar and Virk (1998) suggested that the fluid flow-based conjugate field strategy can also be applied to robot navigation. To demonstrate its usefulness, several simulation studies have been conducted in a variety of tasks (Kadar & Virk, 1998; Virk & Kadar, 1998). These studies, however, focused on autonomous navigation in simulated chemical diffusion fields. In the near future, these findings will be tested on a real platform and other nonchemical sensory mechanisms will also be implemented using the conjugate field approach to autonomous navigation.

### CONCLUSION: TOWARD A FIELD-THEORY-BASED FORMAL FRAMEWORK

Gibson's (1979/1986) last book summarized the final stages of his theoretical development and addressed a variety of ontological, epistemological, and psychological issues surrounding his radical theory of visual perception. Key concepts (e.g., ambient optic array, surface layout, events, affordances, invariants) were discussed in detail but intuitively. Gibson's lack of mathematical formalism was and, in many ways,

still is a barrier to both the further theoretical development and the experimental implementation of his theoretical approach. In fact, whenever Gibson was explicit with regard to any mathematical (or physical) formal concept, he was pessimistic about its potential usefulness.<sup>6</sup> For example, Gibson rejected physical optics as an inappropriate theory for the problems of visual perception and suggested a new discipline, *ecological optics* (Gibson, 1958). Similarly, he denied the usefulness of geometry to describe perceptual space. "I am asking the reader to suppose that the concept of space has nothing to do with perception. Geometrical space is a pure abstraction. . . . Space is a myth, a ghost, a fiction for geometers" (Gibson, 1979/1986, p. 3). Despite his skepticism, Gibson realized the importance of formal techniques in doing science and recognized the potential usefulness of modern systems theory: "What psychology needs is the kind of thinking that is beginning to be attempted in what is loosely called systems theory" (Gibson, 1979/1986, p. 2). However, what kind of formal system would be best suited for Gibson's theory?

Our historical overview revealed that field theory has proven itself to be a powerful analytic technique both in physics and psychology. In physics, field theory has been used to describe various phenomena including spatial as well as spatiotemporal interconnected facts and processes. Nevertheless, field theory was only the beginning of the move away from Newtonian mechanics. Several problems, however, remained unresolved. For instance, understanding the strange behavior of a moving elementary particle in a field required a radically new description. The dynamic interaction between a moving particle and its environmental field required special field equations with complex number (Schrödinger's equation). Actually, this fundamental problem of particle physics has inspired physicists and led to various ingenious solutions within quantum physics. Feynman, for instance, suggested that the existence of all possible particle paths should be postulated to derive the actual movement trajectory based on phase interference among all possible paths (Feynman & Hibbs, 1965; Feynman, Leighton, & Sands, 1968). In short, field theory has been further developed by the introduction of quantum mechanics: a theory that expresses a surprisingly tight interconnectedness between fields and particles as well as physical processes and their measurement.

In psychology, field theory has been used to describe internal neurophysiological processes (Gestalt psychology), the external environment (Gibson's optic flow), and certain aspects of the functional relation between the environment and the actor (Lewin's path analysis, Benedikt's isovist fields). The use of field theory in describing the environment-organism dynamic relation led to the recognition of new problems. Because Gibson was trying to understand the fundamental aspects of this interaction, it is not surprising that his conceptual development is astonishingly similar to the development of physics in our century.

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<sup>6</sup>There is a striking similarity between Lewin's and Gibson's attitude toward contemporary formal techniques.

Gibson's early attempts to describe car driving in terms of field of available safe paths is similar to Feynman's path description of moving particle in a field. In addition, with Gibson's introduction of the optic flow field, a new, powerful analytic tool became available that paved the road for a radically new style of thinking about organism–environment interaction. An optic flow field is generated by a moving organism and has several properties that can be tied to specific tasks; that is, it has several functional properties: Global changes of the optic flow are informative about self-motion (e.g., the center of expansion specifies the direction of rectilinear self-motion), whereas local changes are informative about the relative motion of objects and other forms of change in the environment. In both types of field theories (i.e., field of safe travel and optic flow field), an active intentional agent is implied. To extend field theory to make intention formally explicit by tightly linking perception and action is the main task for contemporary ecological theories.

Our overview has made a case that the fundamental functional requirement for describing any specific intentional behavior is the major challenge facing researchers (Kadar, 1996; Kadar & Effken, 1994; Shaw & Kinsella-Shaw, 1988; W. H. Warren, 1998). It was also suggested that field theory is a necessary tool which should be used but needs to be extended to other techniques as well (Kadar, 1996; Shaw, Flascher, & Kadar, 1995; Shaw et al., 1994).

Several scientists (Harré, 1987; Pribram, 1991; Schumacher, 1986; Shaw et al., 1994) have suggested that of all available formal systems, quantum mechanics is the best suited to address basic problems in perception and that this approach is compatible with ecological psychology. It has especially been noted that the form of laws in ecological psychology, such as Gibson's rules for the perceptual control of action, take the same form as laws expressed in quantum mechanical form. In both cases, the law is defined as a functional connection between information about situations (observations) separated over space–time rather than about material objects or events as in classical laws (Shaw et al., 1994). Although Gabor (1947) elaborated a quantum theory of hearing, in vision there have been only partial results (Daugman, 1985), theoretical considerations (Rosen, 1978), and metaphorical similarities (Schumacher, 1986) rather than a complete quantum theoretical framework supported by strong empirical evidence. A solution to these problems will require development of a sophisticated ecological physics with a formalism capable of doing what no current quantum theory can yet do (Penrose, 1989, 1994; Pribram, 1991; Shaw & Kinsella-Shaw, 1988; Shaw & Turvey, 1999; Turvey & Shaw, 1995).

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