GLOBAL PERSPECTIVES on the ECOLOGY of HUMAN-MACHINE SYSTEMS

VOLUME 1

edited by
JOHN FLACH, PETER HANCOCK,
JEFF CAIRD, KIM VICENTE

GLOBAL PERSPECTIVES ON THE ECOLOGY OF HUMAN-MACHINE SYSTEMS

RESOURCES FOR ECOLOGICAL PSYCHOLOGY

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The publisher has gone to great lengths to ensure the quality of this reprint but points out that some imperfections in the original may be apparent.

To Jimmy

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Preface

"The great mystery, after all, is not the answers that scientists contrive, but the questions they are driven to pose. Why? Why this question rather than another? Why this search, hope, despair, rather than another? Why this ill-lit, nil understood, hobo path? And why the outrageous confidence, born of no evidence, to tred it?"

- Kauffman, S.A. (1993). *The origins of order.* (pp. vii-viii), Oxford University Press.

In the developed world, our ecology is technology. There are few individuals on this planet whose everyday lives are not substantively affected by the action of technical systems albeit at differing levels of sophistication. At the confluence of technology and ecology we see two components of a singular opportunity. The first is the chance to test the principles of ecological psychology against human factors concerns regarding the design and operation of human-machine systems. The second is the chance to pose meaningful questions to the ecological theorist about just which "real" world they choose to focus their efforts on.

The first effort is particularly relevant at present because the information-processing approach, which sets the foundation for much of what we now know as human factors, has broached problems that expose some of the weaknesses of its theoretical basis. Lest some believe us over ardent ecologists, let us state for the record that we still see much that is vital in the information-processing approach, where the nature of the "information" to be processed can be specified with more precision. Further, the wise man does not throw away hard won knowledge and basic understanding in whatever paradigm such understanding is couched, and we would loath to be thought foolish. Indeed, those in human factors are frequently marked by an eclectic pragmatism, especially when the practitioner is "required" to produce an immediate, ready-made answer.

In short, we see the ecological approach as one that offers an alternative view. A view that has provided us with additional insights into how people work with machines. Its value is not as much in the answers it offers, but in the questions it raises.

An eventual integration between information processing and the ecological approach is not one we would rule out and is briefly discussed by several of the authors. However, we believe that examining the human-environment linkage as the basic "unit of analysis" is a critical approach for human factors. Indeed, with its emphasis on action in technical systems, it is central to that enterprise to consider the nature of the context of behavior in which action is embedded. Examining the main effects of human capability is important, but interactions supersede main effects, and situational demands can modify behavior to such an extent that our original knowledge of the isolated human ability might serve to mislead us in richer and more complicated environmental settings.

We are neither priests nor uncritical disciples of the ecological movement. The ecological approach is a strange and curious attractor. Some of us are more attracted than others. Our individual positions range from evangelical to cautiously optimistic, to curious, to argumentatively skeptical. We still have raging arguments among ourselves about some of the basic concepts of the ecological approach. For example, the concept of *affordances* and its theoretical and practical value remains a major bone of contention. We are not above throwing stones at the ecological theorists, some of whom explicitly seem to ignore the world in which humans live and are happier with insects and their intentionality. We have news for those individuals concerning the "real" world.

However, like others in human factors, we have been faced with sometimes critical questions of human behavior in technical systems and, having gone to our cache of theoretical weapons, have found the cupboard uncomfortably bare. Having taken knowledge where we can, we offer the following texts to our companions in the hope that they too might find something useful for their own thoughts and work. This book is directed to behavioral scientists and engineers struggling to design future environments. If you do not already feel as though you are standing on the "edge of chaos," read on. Our goal is to agitate, to stimulate, to challenge, to press the edge of the envelope, to question assumptions that are at the heart of the human enterprise. Insofar as useful information is found or insofar as you are disturbed or unsettled, we in small part, and the authors, in large part, have succeeded. The need and urgency for good human factors applications in a world immersed in technology is obvious. If the following volumes can help to guide and shape the human use of technology to some small degree, we are content that our efforts have been worthwhile.

This work has been produced in two volumes. Volume 1 takes a more global theoretical perspective on human factors and ecological psychology. Volume 2 looks more at local applications of an ecological approach to particular design problems. Across the chapters there is a diverse and sometimes conflicting and contradictory set of perspectives. Ecological theory and its application to human-machine systems is a new and vital enterprise still struggling to adapt and define its niche.

Volume 1 is divided into two sections. The first section provides a selection of theoretical perspectives. Flach opens with a brief historical perspective on the development of an ecological approach to human-machine systems; he attempts to put his own stamp on Gibson's concepts of information and affordance. Hancock and Chignell lay out a set of fundamental principles for the discipline of human factors as an enterprise at the heart of science and technology. Vicente assesses some of the implications for an ecological approach to human factors. This chapter originally appeared in the *Human Factors Bulletin* and received the award as best paper of 1990 from the Human Factors Society. Kirlik's chapter takes inspiration from Brunswik's perspective on ecologically valid research design. He challenges psychologists to a higher level of metacognitive awareness of the intuitions that guide their choice of experimental tasks and stimuli. Rasmussen and Pejtersen integrate a wealth of field experience in domains of nuclear power plant control, information systems, and hospitals into a taxonomic framework to guide generalizations across domains and from the laboratory to the field. Woods, who also has spent much of his career in the wilderness of design and system development, provides a theoretical perspective for the design of representations for supporting communication within the joint cognitive system of human, machine, and work domain. Finally, Flach and Warren present a framework for addressing the emergent properties arising from the interactions of perception and action.

The second section of Volume 1 addresses the central but highly controversial issue of *affordances*. Warren's chapter is a revision of his paper originally presented at the conference on event perception and action. This paper is arguably the first to explicitly consider the concept of affordance and its implication for understanding the "fit" between a human and the built environment. He introduces the concept of *intrinsic measurement* as fundamental to what we mean by "fit." Zaff also considers the implications of affordances for design. He brings a perspective that examines the ability to perceive the affordances of others (a fundamental challenge for designers). Dainoff and Mark examine affordances in the office. They link the concept of *affordances* with Rasmussen's abstraction hierarchy in an attempt to provide a context for asking relevant questions about the design of workstations in the office. Shaw, Flascher, and Kadar extend the concept of *intrinsic* *measurement* and consider the role of the resulting "pi" numbers for understanding the workspace of dynamic, intentional systems. Finally, Bingham and Muchinsky illustrate how the concept of affordances can inform research on the deceptively simple problem of the grasp and control of objects.

The concept of affordance surfaces repeatedly throughout both volumes. Inconsistencies are apparent. However, the hope is that the variance will provide a context against which the invariance (if indeed there is any stability to this concept of affordance) will be revealed. Again, this is a major source of contention and debate among the editors.

In Volume 1, the discussion is often directed at the metaphysical assumptions underlying a science of behavior that can guide the design and development of technology. Arguments are often presented at an abstract general level. These arguments are directed to the academic exercise of defining who we are and why we do what we do. Although this is a necessary and important exercise, it can often be perceived as a "cacophony of sound and fury signifying nothing." Seeing how these arguments translate into the practical concerns of design require no small leap of induction. Volume 2 takes a more practical approach. There we consider specific applications where an ecological approach is stimulating research. Applications range from vehicular control (tractors, automobiles, and aircraft); to navigation and orientation; to display design (process control and virtual realities); to crew coordination; to problem solving and decision making in naturalistic settings.

As with any production of this scope, contributions are made by many who do not get credit as authors or editors. Our sincere thanks to Rob Stephens, Jonathon Sweet, Steve Scallen, and Shannon Skistad for their assistance in production. Thanks to the Ecological Psychology Seminar class at Wright State University for editorial comments on early versions of many of the chapters. Particular thanks to Bart Brickman, Rob Hutton, and Charlie Garness for their editorial comments.

John Flach *Peter Hancock* *Jeff Caird* *Kim Vicente*

RESOURCES for ECOLOGICAL PSYCHOLOGY

Edited by
Robert E. Shaw, William M. Mace, and Michael Turvey

This series of volumes is dedicated to furthering the development of psychology as a branch of ecological science. In its broadest sense, ecology is a multidisciplinary approach to the study of living systems, their environments, and the reciprocity that has evolved between the two. Traditionally, ecological science emphasizes the study of the biological bases of *energy* transactions between animals and their physical environments across cellular, organismic, and population scales. Ecological psychology complements this traditional focus by emphasizing the study of *information* transactions between living systems and their environments, especially as they pertain to perceiving situations of significance to planning and execution of purposes activated in an environment.

The late James J. Gibson used the term *ecological psychology* to emphasize this animal-environment mutuality for the study of problems of perception. He believed that analyzing the environment to be perceived was just as much a part of the psychologist's task as analyzing animals themselves, and hence that the "physical" concepts applied to the environment and the "biological" and "psychological" concepts applied to organisms would have to be tailored to one another in a larger system of mutual constraint. His early interest in the applied problems of landing airplanes and driving automobiles led him to pioneer the study of the perceptual guidance of action.

The work of Nicolai Bernstein in biomechanics and physiology presents a complementary approach to problems of the coordination and control of movement. His work suggests that action, too, cannot be studied without reference to the environment, and that physical and biological concepts must be developed together. The coupling of Gibson's ideas with those of Bernstein forms a natural basis for looking at the traditional psychological topics of perceiving, acting, and knowing as activities of ecosystems rather than isolated animals.

The purpose of this series is to form a useful collection, a resource, for people who wish to learn about ecological psychology and for those who wish to contribute to its development. The series will include original research, collected papers, reports of conferences and symposia, theoretical monographs, technical handbooks, and works from the many disciplines relevant to ecological psychology.

Series Dedication

To James J. Gibson, whose pioneering work in ecological psychology has opened new vistas in psychology and related sciences, we respectfully dedicate this series.

Chapter 1

The Ecology of Human-Machine Systems: A Personal History

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I first became interested in the ecological approach to psychology when, as a graduate student at Ohio State, I heard Rik Warren describe the properties of flow fields and how they might be specific to properties of locomotion such as heading, altitude, and speed. It occurred to me that these descriptions of optical structure may have far more relevance to understanding a skill, such as landing a plane, than the changes in slope or intercept of a reaction time function that were, at that time, central to the chronometric analyses of mind that dominated much of my graduate training (even though these reaction times may have been measured while the operator was simultaneously flying a simulator). As I learned more about the ecological approach it seemed obvious to me that challenges such as understanding automobile driving and flight were important to the evolution of Gibson's theories about behavior. It was surprising to me that those interested in human factors and those interested in ecological approaches to behavior were not actively embracing each other's theories and problems. However, I have always tended to underestimate the inertia in systems. Although the merging of ecological theories and human factors challenges has not happened as quickly as I expected, I think there is a gradually accelerating movement toward communion. This book is perhaps evidence of this movement and will hopefully be a stimulus to encourage a continuing movement toward communion.

To set the stage for this book, I would like to briefly present my personal perspective on the events that have made such a book inevitable. To begin, as I mentioned earlier, the obvious roots for a union of human factors challenges with ecological perspectives are Gibson's early works on automobiles (Gibson & Crooks, 1938) and his work in aviation (Gibson, 1944,1947/1958; Gibson, Olum, & Rosenblatt, 1955). However, Gibson was not alone in his insights. Langewiesche (1944), in his analysis of the information for landing and approach, anticipated many of the ideas about optical sources of information for controlling flight. Also, the need for an ecological approach, that is, an analysis whose scope is the human environment as a system, was voiced by Taylor (1957) as he described the importance of research on human-machine systems for the future of basic psychology:

> *"It drew attention to the fact that in many circumstances the behavior of the man was inseparably confounded with that of the mechanical portions of his environment. This meant that psychologists often could not study human behavior apart from that of the physical and inanimate world - that all along they had been studying the behavior of man-machine systems and not that of the men alone. The inseparability of the behavior of living organisms from that of the physical environment with which they are in dynamic interaction certainly argues against maintaining separate sciences and construct languages: one for the environment, the other for that which is environed."* (Taylor, 1957, pp. 257-258)

One of the earliest papers, other than Gibson's, to analyze the information in optic flow relative to vehicular control was David Lee's (1976) paper, "A Theory of Visual Control of Braking Based on Information About Time-to-Collision." In this paper, Lee introduced the higher order optical variable tau. Lee wrote:

> *"A mathematical analysis of the changing optic array at the driver's eye indicates that the simplest type of visual information, which would be sufficient for controlling braking and would also be likely to be easily picked up by the driver, is information about time-to-collision, rather than information about distance, speed, or acceleration/deceleration. It is shown how the driver could, in principle, use visual information about time-to-collision in registering when he is on a collision course, in judging when to start braking, and in controlling his ongoing braking."* (p. 437)

Perhaps, the first laboratory dedicated specifically to an ecological approach to problems of human-vehicular systems was not established until the late 1970s and early 1980s. During this time, the Aviation Psychology Laboratory at Ohio State was under the direction of Dean Owen. Dean assembled the components for a visual flight simulation system to evaluate the optical flow field as a source of information for flight control. During the 1980s, a number of theses and dissertations evaluated sources of information for judgments about altitude and speed. Much of this research is reviewed in a chapter written by Owen and Warren (1987) in *Ergonomics and Human Factors: Recent Research* (Mark, Warm, & Huston, 1987). Many of Owen's students have gone on to continue active research careers in Aviation Human Factors. I was lucky to be on the fringes of this group during my graduate training at Ohio State in the early 1980s. This association had a major impact on my future research agenda.

The analysis of optical information specific to vehicular control continues to be one of the areas of active interchange between ecological theory and human factors problems. In 1986, Rik Warren and Alex Wertheim organized an international workshop on the perception and control of self-motion held at the Institute for Perception TNO, Soesterberg, The Netherlands. This workshop brought together a diverse group of researchers, and although many among the group would not consider themselves "Gibsonian," the influence of Gibson's work was clearly evident. This workshop led to the publication of a book, *Perception and Control of Self-Motion* (Warren & Wertheim, 1990). In Spring of 1989, Walt Johnson and Mary Kaiser hosted a workshop on Visually Guided Control of Movement at the NASA Ames Research Center, Moffett Field (Johnson & Kaiser, 1990). Many important issues with regard to the nature of information in optic flow and the importance of the coupling between perception and action were discussed at this workshop (see also Flach, 1990a).

Outside the area of vehicular control, Warren's paper, "Environmental Design as the Design of Affordances," presented at the Third International Conference on Event Perception and Action, Uppsala, Sweden (1985), was a landmark in the merging of human factors with ecological theory. Warren writes:

> *"Analyzing an affordance requires a task-specific description of an ecosystem that considers the relevant organism and environmental variables and the biomechanics of the task. The fit between organism and environment must be measured relationally, using methods of*

intrinsic measurement, and can be characterized in terms of optimal points at which performance is most efficient or comfortable, and critical points, at which performance breaks down." (p. 2)

The role of intrinsic measurement as a basis for scaling the affordances in artifactual environments has become a cornerstone for building ecological theories of the workplace (see also Mark, 1987; Mark & Voegele, 1987, Warren, 1984, 1987; Warren & Whang, 1987). In 1988, *innovation,* which is the journal of the Industrial Designers Society of America, featured three articles that address the concept of intrinsic measurement and its importance for design (Mark & Dainoff, 1988; Rutter & Newell, 1988; Rutter & Wilcox, 1988).

Another important area of research that has seen the impact of an ecological approach is the problem of interface design for process control and decision support. Dave Woods was one of the first to bring ecological theory to bear on this problem. At a NATO Advanced Study Institute on Intelligent Decision Aids in Process Environments, Woods (1986) wrote:

"The important point for the development of effective decision support systems is the critical distinction between the available data and the meaning of the information that a person extracts from that data (e.g., S. Smith 1963). The available data are raw materials that the observer uses to answer questions (questions that can be vague or well formed, general or specific). The degree to which the data help answer those questions determines the informativeness or inferential value of the data. Thus, the meaning associated with a given datum depends on its relationship to the context or field surrounding the data including its relationship to the objects or units of description of the domain (what object and state of the object is referred to), to the set of possible actions and to perceived task goals (after Gibson, 1979, what that object state affords the observer). The process is analogous to figure-ground relations in perception and shows that information is not a thing-in-itself but is rather a relation between the data, the world the data refers to, and the observer's expectations, intentions, and interests. As a result, informativeness is not a property of the data field alone, but is a relation between the observer and the data field." (p. 163)

Rasmussen (1986) also references Gibsonian theory in his book, *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering.* Rasmussen wrote:

"As I understand Gibson's concept of direct perception, the "dynamic world model" is in the present context very similar to the mechanisms needed for the "attunement of the whole retino-neuro-muscular system to invariant information" (Gibson, 1966, p. 262), which leads to the situation where "the centers of the nervous system, including the brain resonate to information." This selective resonance relies on the existence of a generic dynamic model of the environment. The implications of Gibson's view of perception, as based on information pickup instead of sensation input, are in many ways compatible with [my own model]. To Gibson, perception is not based on processing of information contained in an array of sense data. Instead the perceiver, being attuned to invariant information in space and time in the environment, samples this invariant information directly by means of all senses. That is, arrays of sense data are not stored or remembered. They have never been received; instead the nerve system "resonates." In my terms, the world model, activated by the needs and goals of the individual, is updated and aligned by generic patterns in the sensed information, but the idea of an organism "tuning in" on generic time-space properties is basically similar and leads to the view of humans as selective and active seekers of information at a high level of invariance in the environmental context. The subconscious dynamic world model or the attunement of the neural system leads to the situation where primitive sense data are not processed or integrated by symbolic information processes as Minsky suggests, but the generic patterns in the array of data in the environment are sampled directly by high-level questions controlling the exploratory interaction involving all senses." (pp. 90-91)

The Fourth International Conference on Event Perception and Action at Trieste in 1987 included a symposium chaired by Sebastiano Bagnara entitled "Errors in Human-Machine Interaction." Presenters included Mancini, Rasmussen, Reason, and Vicente. However, almost no one except for the presenters and myself attended this session. However, this insulation from the rest of the conference helped to cement a close bond between myself, Vicente, and Rasmussen which has greatly influenced my thinking about how to attack the problems of interfaces in complex systems. The ideas presented by Rasmussen and Vicente led to a paper published in the *International Journal of Man-Machine Studies* (1989) — "Coping with Human Errors Through System Design: Implications for Ecological Interface Design."

It is notable that Norman in his popular book *The Psychology of Everyday Things* (1988) adopted Gibson's term affordance. He wrote:

> *"There already exists the start of a psychology of materials and of things, the study of affordances of objects. When used in this sense, the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used."* (p. 9)

A careful reading of Norman's presentation shows that it is somewhat at odds with Gibson's view of affordance (in a footnote, Norman clearly acknowledges the conflict between his view and Gibson's view of affordance). Norman confuses the affordances of an object with the information that specifies the affordances. For example, he writes that "affordances provide strong clues to the operations of things" (p. 9). Clearly, Norman is moving toward an ecological approach, but there is still a strong influence of the more traditional information processing approach, in which meaning must be constructed from the clues available. This is somewhat reminiscent of Neisser's transition from *Cognitive Psychology* (1967) to *Cognition and Reality* (1976). Just as with Neisser, this revision in thinking will likely disturb traditional cognitive psychologists, but will not be satisfactory to many already entrained in the ecological approach. This probably applies, as well, to Woods and Rasmussen's work. However, it is encouraging to see a number of significant contributors to the development of cognitive engineering moving somewhat in the direction of an ecological approach.

Although many will strongly object, I think that this movement toward a middle (perhaps higher) ground is healthy for our science. One of the benefits of the challenge in applying psychology to problems of human-machine systems (as opposed to conducting research exclusively within narrowly defined experimental paradigms or toy laboratory worlds) is that it provides an acid test for dogmatism of any sort. More than anything these challenges teach humility and open-mindedness.

In summer 1989, a symposium was organized for the Fifth International Conference on Event Perception and Action at Miami University entitled "The Ecology of Human-Machine System." Presenters included Stappers and Smets, Woods, Moray, Kugler, and Vicente and Rasmussen. This session was very well attended and stimulated much interesting discussion. I think that most notable were some challenges from Stappers and Smets about how to go beyond purely kinematic models of optic flow. This is particularly significant to my thesis here, as these important theoretical issues were being raised from within a department of industrial design engineering. It is important to see that applied problems are beginning to reflect back in a way that challenges our theories and advances our basic science of behavior. This is a theme that Taylor (1957) emphasized as one of the promises of engineering psychology. Several publications resulted from this symposium (Flach, 1989; 1990b; Vicente & Rasmussen, 1990).

It is important for us to realize that hypothesis testing is not the only way to validate our theories. Design of products and the success or failure of those products is another way of validating the implicit and explicit theories that guided the design. Whereas hypothesis testing emphasizes internal validity, design emphasizes external validity. Good science demands a balance between these two forms of validity. Kirlik's chapter (this volume) discusses design as experiment. Also, I think the work of the Form Theory Group at Delft demonstrates this alternative quite well (see Smets, 1994). The key difference between their work and work of other design groups is the explicit role perceptual theory plays in their designs.

In 1990, the problems of human-machine systems were discussed at both the International Society of Ecological Psychology's Spring meeting in Champaign-Urbana, at which Alex Kirlik's discussion of the affordance properties of a complex helicopter control scenario stimulated much interest, and at the First European Meeting at Marseille which included presentations by myself, John Paulin Hansen from RISO National Laboratory in Denmark, and several presentations from the Industrial Design Group at Delft Technical University. Also, in 1990, Vicente wrote an article entitled "A Few Implications of an Ecological Approach to Human Factors," that was published in the *Human Factors Society Bulletin*. It was awarded the best paper award at the 1991 annual meeting of the Human Factors Society.

A symposium entitled "An ecological approach to human-machine-systems" was held at the 1992 Annual Meeting of the Human Factors Society (Flach & Hancock, 1992). Presentations were given by myself and Peter Hancock and a panel of reactors included Alex Kirlik, Frank Moses, Donald Norman, and Kim Vicente. This symposium was filled to overflowing and elicited a largely enthusiastic response from the audience. A criticism of the presentations was that they were too abstract. People wanted more practical examples of how an ecological theory can affect how they approach design problems. We hope that this book will provide a more balanced presentation with attention to both the theoretical and the practical implications of an ecological approach.

This is a biased and necessarily brief history of the growing attention that ecological theory is getting with respect to applications in human-machine systems. I apologize to those whose contribution I have failed to acknowledge. I consider myself fortunate to have been swept up in this current of ideas. It is our hope that this book captures others who have an interest in taking experimental psychology beyond the laboratory. The ecological approach promises a basic science that does more than play 20 questions with nature (Newell, 1973), which is not mere puzzle solving. It promises a basic science that will be able to inform and guide us as we shape an environment within which we can thrive.

To conclude this chapter, I address the two most critical (and perhaps the most misunderstood) concepts of an ecological approach to psychology; *affordance* and *direct perception*. First, I address the concept of affordance. In order to talk about human-environment systems, a language for describing the environment is needed. Traditionally, psychology has looked to classical physics for that language. The language of classical physics, which describes objects in terms of grams, centimeters, seconds, and so on, was chosen explicitly so that descriptions of the objects were observer independent. This strategy has been very successful, but has a limited scope, even for describing the physical world (e.g., at the level of quantum mechanics this strategy leads to some puzzling contradictions such as the dual particle/wave nature of light). Gibson (1979) opted for a different strategy that he calls ecological physics. This strategy adopts a language that is observer dependent for describing the environment. Thus, the world is described as graspable, walk-on-able, sit-on-able, pass-through-able, step-on-able, climb-over-able, and so on. This kind of description is better suited to the study of *perception,* which is about the relation between the observer and the environment. This type of description has the promise of capturing the "meaningful" or "functional" properties of the environment. Whereas the traditional dimensions from classical physics are afunctional. Meaning requires further processing (e.g., a computation of the ratio between the object's size in centimeters and the size of my own hand in centimeters). Classical physics was designed to describe the environment independent of an observer. Ecological physics is designed to describe the environment relative to a specific observer.

Thus, the underlying assumption is that biological systems perceive the world, not on the basis of extrinsic units (e.g., centimeters) that need to be processed before they are meaningful, but in terms of intrinsic units such as eye height, leg length, or hand size that have explicit meaning for the system. If this assumption is true, then for us to understand perception we must also be able to describe the environment in similar terms. Thus, an ecological physics is required. Note that this is a realist approach. The properties of the environment are not mental constructions. However, the measurement scale we use to describe these properties is a theoretical construction of the scientist. Whether we scale the properties of the environment in terms of inches, centimeters, or hand size does not make the size of the object less real. For classical physicists the observer-independent properties are most useful in their efforts to build a description of the world in terms of observer independent laws. For psychology, however, the goal is to discover the observer dependent laws (i.e., the laws that relate observers to the environment). An ecological approach starts with the assumption that these laws can best be discovered using an intrinsic measurement scale that captures the functional properties of the environment (i.e., affordances).

The second concept is that of direct perception. The issue here is whether the mapping between structure in a perceptual field (e.g., an optic array) and affordances in the environment are specific or not. Direct perception requires that these mappings are specific. To the extent that the mappings are specific, then the observer can directly pick up the affordances in the environment. A theory of direct perception does not require that there are absolutely no ambiguities for an observer (even though the mapping between the perceptual field and the affordances is specific, the observer may not be skillful in picking up the structure). A critical distinction between traditional and ecological approaches, however, is how ambiguities are resolved. A direct perceptual system resolves ambiguities through acting on the environment (looking, touching, manipulating, etc.), rather than through indirect means such as inferring, computing, or assuming.

For building an ecological approach to human-machine systems it is not necessary to uncritically accept the dogma of direct perception. Rather, I think that direct perception poses two fundamental challenges for cognitive engineering. First, in trying to understand skilled behavior (e.g., vehicular control, naturalistic decision making), the concept of direct perception challenges us to evaluate the structure of the perceptual fields to see whether we can find specific mappings to functional properties of the task and second to see if there is a correlation between the structures in the perceptual fields and the actions of a skilled operator. As Neisser (1987) noted:

> *"If we do not have a good account of the information that perceivers are actually using, our hypothetical models of their "information processing" are almost sure to be wrong. If we do have such an account, however, such models may turn out to be almost unnecessary."* (p. 11; also cited in Vicente, 1990)

The first challenge when modeling skilled performance is to avoid mentalistic constructs whenever possible. The second challenge is in the area of the design of interfaces. Previously, I have characterized the problem of display design as inverse ecological optics (Flach, 1988). Ecological optics is the study of the structures within reflected light (i.e., the optic array) that are specific to properties of environments and observers (e.g., time to contact). Display design is the creation of a perceptual array, the structure of which maps directly to (specifies) the functional properties of the work domain. Thus, the challenge is to build an interface that can support direct perception. The implication is that a poor interface is one in which ambiguities can not be resolved by activity of the observer, where assumptions, computations, and inferences are required. Vicente and Rasmussen (1990); and Rasmussen and Vicente, (1989) called this the problem of ecological interface design. Where traditionally there has been much concern with building interfaces that match the operator's "mental model," ecological interface design focuses on matching the structure in the interface to the natural constraints of the work domain in a way to inform and guide the operator as he navigates within that work domain. With an ecological interface the need for assumptions, computations, and inferences (and perhaps for a mental model) are reduced or eliminated all together. Thus, I recommend that we consider direct perception as a possibility, which can be realized whenever there are specific mappings between structure in a medium (e.g., optic array or electronic display) and the affordances available to a behaving system.

The concepts of affordance (meaning) and direct perception (specificity of information in sensory arrays) will arise repeatedly throughout this volume. By the end of this book, you may have a more informed and richer understanding than my own. And perhaps will be better prepared for the challenges of shaping our future in a technological world.

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Chapter 2

On Human Factors

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The Secret of Machines

We can pull and haul and push and lift and drive,
We can print and plough and weave and heat and light,
We can run and race and swim and fly and drive,
We can see and hear and count and read and write...

But remember please, the Law by which we live,
We are not built to comprehend a lie.
We can neither love nor pity nor forgive -
If you make a slip in handling us, you die.

2.0 Introduction and Overview

This chapter develops a descriptive theoretical structure for human factors. The structure is based on a view of technology as the principal method through which humans expand their bounds of perception and action but also as the medium through which control is arbitrated in systems of increasing complexity and abstraction which explore the new 'territory' revealed. The theory presents a broad rationale for the contemporary impetus in human factors and historical motivations for its growth. It is suggested that human factors is unlike other traditional divisions of knowledge and is more than the mere haphazard interdisciplinary collaboration between the engineering and the behavioral sciences. In identifying the opportunities and constraints intrinsic to emergent dynamic operational spaces derived from the interplay of human, machine, task, and environment, we point to a future for human factors as the essential link in the co-evolutionary development of biological and nonbiological forms of intelligence, the failure of which will see the certain demise of one and the fundamental impoverishment of the other.

'Science above all things is for the uses of life.'

2.0.1 Preamble

Rudyard Kipling's "The Secret of Machines," is as appropriate for the supervisor of contemporary complex systems as it was for the individual worker in the 19th century factory. Slips in handling machines can and do lead to fatal consequences. Yet, we have built a global society whose dependence on such systems grows daily. Human factors is at the heart of this development, seeking on the one hand to maximize the benefit derived from technology, while on the other, exercising a continual vigilance over its darker side. In what follows, we present a framework that views human factors as something more than a convenient fusion of knowledge from disparate disciplines. What emerges is no traditional academic pursuit. Rather, as the above quotation from Francis Bacon intimates, it reveals human factors arguably as the motivation of science and by extension at the very heart of the human enterprise itself.

2.1 Structure and Aims of This Chapter

Human factors is frequently represented as a discipline that makes science and technology more appropriate and palatable for human consumption. However, Bacon's view of science suggests that human factors should not simply ameliorate the adverse impact of technology after the fact. Human factors should be seen to motivate science, engineering, and systematic empirical human exploration in the first place.

In order to provide definitive motivation for science, human factors must present a clear vision of what the "uses of life" are. We need to understand how people use perception, cognition, and action to decide on goals and carry out meaningful and useful tasks in the pursuit of those goals. This necessary understanding includes a rational analysis of tasks, a psychological analysis of human behavior and capability, and an engineering analysis of how humans interact with tools and systems in performing these tasks in differing environments. It should also include purposive and proactive accounts that are consistent with the requirements for explaining goal-oriented reasoning and behavior.

Therefore, we address the question of how humans use technology in the goal-oriented and task-oriented exploration and manipulation of their perceivable environment. Powers (1974, 1978) has indicated that behavior is a goal directed process that is organized through a hierarchy of control systems. Higher-order systems perceive and control an environment composed of lower-order systems, with only the first-order systems interacting directly with the external world. Human behavior has been characterized as an inner loop of skilled manual control and perceptual processing which is embedded within an outer loop of control that includes knowledge-based problem solving. Moray (1986), for instance, gives the example of a nested series of goals working from an extreme outer loop (influencing society and raising children) to inner loop processes such as controlling the position of a car's steering wheel in order to drive that car to a destination.

In this chapter, we explore human capabilities for perception and action and the role of technology in redefining the bounds and the nature of those capabilities. We also examine the linkage between perception and action and the way in which that relationship is changing as both actions and perceptions are elaborated by evermore sophisticated technologies. Initially, we generate a description of the limits to unaided and aided action and contrast these with bounds to unaided and aided perception. We suggest that the "tension" which results from the disparity between what can be perceived compared with what can be controlled provides the major motivational force for human exploration.

In respect of such exploration, technology generates the dual but opposing effects of increasing the range of action while simultaneously expanding the range of perception. The further these respective bounds are extended, the more complex (Hancock, Chignell, & Kerr, 1988) are the technical systems needed to support exploration and the more reliance, at the present time, is placed on metaphorical representation of the control spaces involved. In elaborating our overall theme we use a relativistic framework to describe the expanded vista of capability that accompanies the sequence from homeothermy, through tool genesis

(Oakley, 1949), and intelligent prosthetics, to the contemporary potential for a 'supercritical' society.

In examining a further duality of technological innovation, we contrast the potential for catastrophic failure that accompanies transition at the edge of chaos, with the knowledge that we cannot 'directly will to be other than we are.' While articulating the constraints on human nature and ability, we are also augmenting our basic abilities as we systematically explore and engineer our environment to 'create' our future selves. Our future selves are bound to the co-evolution of biological and non-biological forms of life. Intrinsic to our whole argument is the centrality of ecological principles and in particular the goal-oriented interaction between humans and the perceivable environment as the basic unit of analysis for human factors.

1. The perception-action link may explain *how* humans explore the environment. The perception-action gap may explain *why* they explore the environment.

2.2 PERCEPTION AND ACTION IN SPACE AND TIME

It may be observed that the personal and collective odyssey of humankind is to find and establish our respective place in space and time. While this journey might be considered from one perspective as an artistic endeavor, we focus here on the task-oriented use of technology to provide a degree mastery over the perceivable environment as parsed by the constructed metrics of space and time.

The exploration of space and time is motivated by goals, which can be expressed as desired future states of the environment, and evaluated by the associated perceptual experience that they engender. Strategies are ways of achieving goals, and tasks are the steps by which goals are achieved (see also Shaw & Kinsella-Shaw, 1989). While a goal is a desired future state of a system, a task is a subsidiary component that implies a specific transformation. Goal achievement is composed of the successful and integrated completion of more than one task. Actions which subsume tasks transform the state of the world. From a thermodynamic perspective, actions typically result in a disturbance to local entropy (Swenson & Turvey, 1991) and the expenditure of energy toward a more ordered[1] state of the system. Thus temporal direction is apparently implied in the performance of tasks. Simple temporal progression of a system without alteration cannot be regarded as a task within this definition.

The cost of transformation, or demand of any task may not be specified *in vacuo*. In human performance such costs are typically expressed as a function of the time taken to traverse from initial state to goal state and the accuracy of that transition, in essence space-time synchronization. Transformation cost can also be expressed in terms of effort. Machines, as creators and manipulators of energy, act to increase the number of possible paths by which a specific goal can be achieved. Technology thus serves to broaden the horizon of the possible. While machines serve to open the window of opportunity, environmental constraints frequently frame and limit what is possible.

The environment often presents hurdles and obstacles that the operator anticipates. Indeed one hallmark of expertise is the ability to project expected demands and preempt their more adverse consequences. However, the environment can also present unexpected perturbations which interrupt on-going tasks and can, under certain circumstances, pervert goals altogether by removing them from the range of possible outcomes. With respect to operations then, human-machine systems seek to expand ranges of possible activity while the environment restricts that activity. Unfortunately, this antagonistic aspect of interaction has permeated much design. Thus systems often seek to conquer and control the environment, rather than recognize and harmoniously incorporate intrinsic constraints. (Although conquering nature should be acknowledged as a predominantly Occidental pre-occupation, see McPhee, 1989). Ultimately, it is the ability to recognize and benefit from mutual constraints and limitations to action that characterizes "intelligence" on behalf of systems.

Goal-oriented behavior is defined in part by reacting to

[1]A question for the second law of thermodynamics is the intrinsic appointment of a normative arbiter who dictates what connotes order and therefore the distinction between 'more' and 'less' ordered. While this arbiter is conjured by the physicist the problem of ordering is apparently obviated. However, if the arbiter is invoked by the psychologist, the perceived nature of order becomes more equivocal as does entropy and by extension, time. The same question can be extended to the first law where we might ask whether burning a piece of ink-splattered paper is the same as setting fire to the U.S. Constitution, a document which embodies both informational and societal significance. While the physical effect may be identical, for human observers they are certainly not perceived as equivalent events. (see also Gibson, 1975)

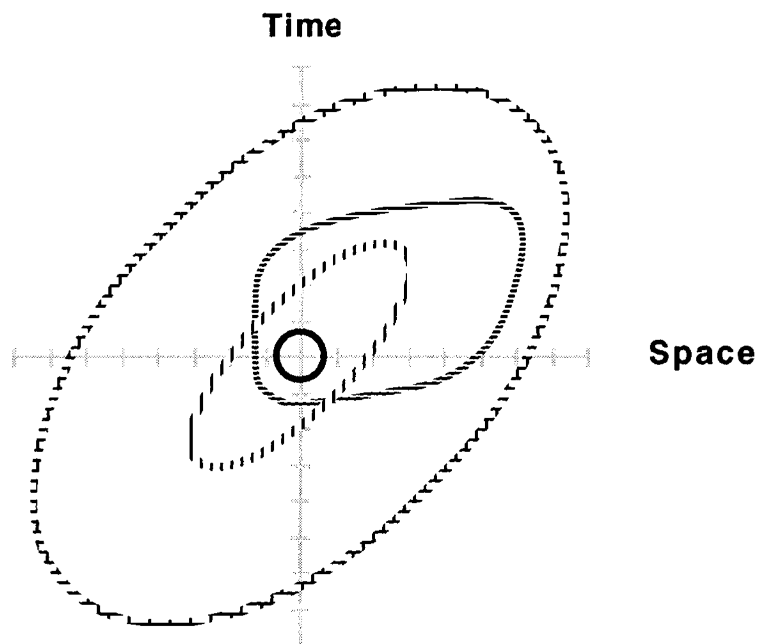

Figure 2.1. *Human-range (the inner circle), perceptual-range (the horizontal line envelope), prosthetic-range (the vertical line envelope), and universal-range (the outer envelope) expressed as functions of space and time*[2]*. Note that these regions are approximations and are not drawn to represent definitive boundaries.*

environmental constraints that limit the range and effectiveness of perception and action. Despite the arbitrary nature and the relativity of space and time, the limitations of perception and action can be considered initially within a framework that views space and time, artificially, as orthogonal. The environment may be scaled from the small to the large and the brief to the prolonged. Within these continua there are relative ranges of space and time with respect to our own size and our own perception of duration. A representation in terms of orders of magnitude is given in Figure 2.1. We place ourselves at the origin and it can be observed that our collective recorded history is an account of

[2]Scales of spatial representation are clearly illustrated in the text *Powers of Ten* (Morrison, Morrison, Eames, & Eames, 1982). It is of course interesting to note that these authors achieved their illustration by fixing the orientation of one axis and subsequently adjusting the bounds of the remaining axes. Hence, *three-dimensionality* is strongly, if intrinsically emphasized. It is also clear that there is no equivalent temporal Powers of Ten. Indeed, it is an instructive exercise in imagination to attempt its construction. The reader is invited to do so.

Scale (sec)	Time Units	System	Level of Interaction
10^{7}	months		
10^{6}	weeks		Society
10^{5}	days		
10^{4}	hours	Task	
10^{3}	10 min	Task	Work Group
10^{2}	minutes	Task	
10^{1}	10 sec	Unit Task	
10^{0}	1 sec	Operations	Cognition
10^{-1}	100 ms	Acts	
10^{-2}	10ms	Neural Circuit	
10^{-3}	1ms	Neuron	Neurophysiology
10^{-4}	100 microsec	Organelle	

Figure 2.2. *A time scale of human actions (After Newell, 1990).*

our physical, but not spiritual, displacement from this central location. (see also Gooddy, 1988).

Human response in spatial dimensions has been studied extensively, particularly in psychophysics. Fine spatial discrimination can be measured by Vernier acuity in vision, two-point threshold for touch, and auditory spatial localization and discrimination in hearing.

Human interest in the dimension of time has a particularly long history, going back to the use of astronomical tables in early religion and agriculture (Fraser, 1966). Due to the need to coordinate and synchronize the actions of a large number of people and things, the social importance of temporal scaling is now reflected in the omnipresence of timekeepers. Figure 2.2 (after Newell, 1990) shows part of the time axis of Figure 2.1, interpreted in terms of human action (see also Iberall, 1992, p. 45).

2.2.1 *Humanrange*: Boundaries To Unaided Action

One of the initial lessons in comparing the range of human perception and action with the entire range of space-time is that direct human experience is a relatively small subset of the entire space-time continuum. In defining the boundary of *humanrange* we can begin by indicating the limits of unaided action on the spatial axis. Unaided is here meant to signify without the assistance of other entities including natural or manufactured tools or machines. It is clear, given the physical constraints of our musculo-skeletal system, that unaided we cannot directly manipulate objects less than some fractions of an inch in size. Also, in respect of an upper boundary, we might be able to throw a stone some hundred yards or so but without some form of assistance we could not exceed this distance to any great degree. We should note immediately that the specification of this spatial boundary include intrinsic temporal assumptions. That is, throwing the stone implies a force exerted over a short duration. As becomes immediately apparent spatial constraints cannot be specified independent of time and vice-versa and this mutuality is as important for the behavioral sciences as it is for the physical sciences (Locke, 1690; and see also Hancock & Newell, 1985). With respect to the boundaries of time, the lower threshold can be viewed as the duration which divides the performance of two separate acts. The upper temporal boundary is, putatively, the length of an individual's lifetime. However, this latter definition, like each of the others, may not go unchallenged. It is a defendable assertion that humans leave partial representations of themselves through communication, procreation, or *re*creation.

Even over a lifetime, unaided by any tools or prosthetics, a human may achieve a considerable manipulation of the environment. However, history informs us that few existing archaeological monuments were not constructed without the use of the then existing highest state of technology. Indeed it might be argued that no totally unaided human manipulations of the environment have survived prolonged periods. It is clear that in the overall picture, the spatial and temporal dimensions are interdependent and the collective range over which an unaided human may exert action (*humanrange*) is highly restricted in comparison to the limits of unaided perception to which we now turn.

2.2.2 *Perceptualrange*: Boundaries to Unaided Perception

If the boundaries to unaided action are relatively restricting, the same cannot be said of the boundaries of unaided perception or *perceptualrange*. We will deal first with perception at the lower bounds. The lower temporal boundary is usually represented by events that are separated by fifty to one hundred milliseconds in duration (Stroud, 1955, see also Poppel, 1988, but see Vroon, 1974). This period is projected to represent the perceptual moment (but see Gibson, 1975) or in the terms given by Clay (cited by James, 1890) and subsequently Minkowski (1908), the 'specious present.' Depending upon what it is we wish to observe, various limits to spatial perception might be suggested. Unaided, the human observer can see objects down to quite small sizes

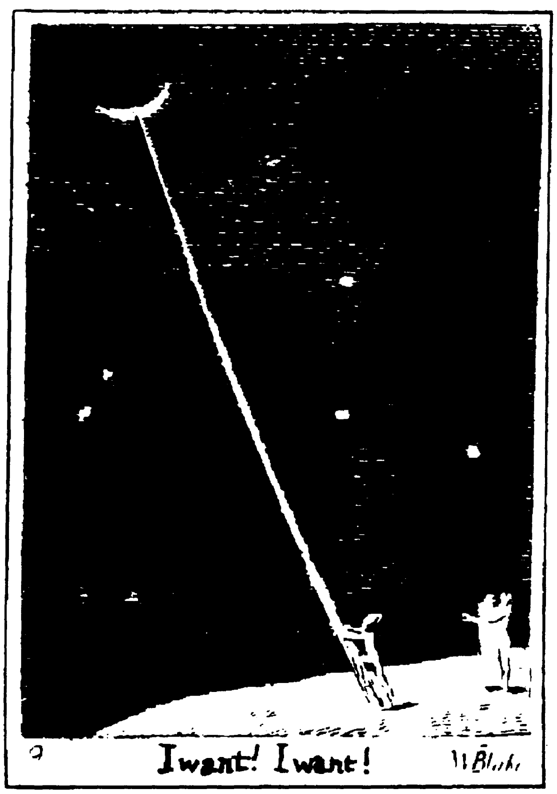

Figure 2.3. *William Blake represents the eternal reaching of human nature in the illustration "I want, I want."*

and from their actions infer the presence of even smaller particles. However, without aid, empirical microbiology might be somewhat limited as illustrated in one of Gary Larson's wonderful cartoons. But it is not the lower bounds of space and time, nor even the upper temporal boundary that represent such a vast contrast with action limits. Rather it is the bounds to unaided spatial perception. As can be seen from the superimposed envelope of *perceptualrange* in Figure 2.1, it is the vast regions of space which we may perceive unaided, but over which we cannot act that represents the major disparity. It is therefore no coincidence that astronomical observation provided the major early impetus for what we now recognize as the scientific enterprise (Koestler, 1959).

It is, we suggest, the 'tension' created by this dissociation between perception and action that provides a basic motivation for exploration. The contemporary vehicle for such exploration is applied science in the form of technology. 'Reaching' as the metaphor for exploration and knowledge is not new and nowhere is this urge more clearly represented than in the illustration by William Blake, reproduced in Figure 2.3. In this picture he expresses the essence of the human desire to reach beyond frustrating restrictions on action. Here again we see that Blake's example is taken from the large scale of space, a reaching toward the nearest celestial body (the moon). Our manifest inability to exercise influence over far distant objects has been clear for many millennia. The plethora of non-holonomic overtones in Blake's illustration have been explored by others (see Bronowski, 1958), however, there yet remains more irony and pathos to be distilled.

2.2.3 *Prostheticrange*: Boundaries to Aided Action

With respect to the process of exploration and manipulation of the environment with the aid of external implements, technology has always served two antagonistic purposes. As we observed earlier, tools have increased the ranges of space and time over which an individual may act. However, their use also results in the furtherance of the boundaries of the regions of space and time which can be observed. With respect to aided action, the envelope is expanded some orders of magnitude over the meager range of unaided exploration. Contemporary boundary markers to this *prostheticrange* are represented by elementary particle manipulation in the lower spatial range to the Voyager Spacecraft and its physical presence beyond the edge of the solar system at the upper spatial range. It might be argued that humankind has exercised influence over a much larger range when we consider the information intrinsic to radiowaves that have left this planet within the last century. The choice of the precise nature of which physical manipulation is used as a criterion is one that may be challenged. However, as this simply extends the envelope by some multiple it is not a question to which we direct particular concern here.

On the temporal scale, we have become familiar with picosecond-based measures (Rifkin, 1988) at the lower boundary, while storage and dynamic knowledge representation of expert systems promises the use of technology to preserve at least a small portion of individual knowledge or expertise beyond our traditional lifespan (Moravec, 1988). It may further be argued that procreation, *re*creation, and information communication through traditional media also perpetuate some portion of many individuals. According to allometric scaling, humans should live on average to 27 years of age (see Schroots & Birren, 1990; and Yates, 1988). Already, our use of technology staves off death more than three to four-fold our expected life-span. Also, there is a trend with improvements in nutrition, personal fitness, and medical faculties for individuals to live even longer. However, it is one of the basic human characteristics to countenance one's own demise. In spite of limits on individual perception of spans of time, the same scale for upper temporal boundaries cannot be applied to the things we create with technology. We have direct evidence that the constructions of our forebears have lasted several thousand years and we project that our own manipulations might last into the hundreds of thousands of years (e.g., nuclear waste). However, it is important to distinguish, at a number of levels, between mere persistence of effect versus creative and generative actions.

2.2.4 *Universalrange*: Boundaries to Aided Perception

Outside prosthetic scale, we have located *universalrange*. This represents the boundaries of what we may perceive when aided by technology. In essence, it represents the known universe and like other envelopes is still at present expanding (that is our knowledge of it is still expanding, whether there is and/or will be continued physical expansion is a question upon which cosmologists seem unable to agree). An individual looking out into space is looking back in time. The interdependence of space and time has been recognized by physicists for over three centuries, while this combination (space-time) has also been explored with respect to human behavior (Hancock & Newell, 1985). We use this approach to pursue our argument below. With the aid of contemporary technology our range of perception is vastly increased. The resolution of the Hubble telescope promised to expand *universalrange* and improve our knowledge of entities between ourselves and that threshold. Like other forms of expensive and complex technical systems it proved unfortunately vulnerable to failure (see Perrow, 1984; Reason, 1990). At the aided lower end of the spatial scale, where observation fades through metaphor to concept, we have begun to recognize the interaction of the conceivable, the perceivable, and the fusion of the potential with the actual. Comparable recognition at the other extreme boundary of space-time would represent a significant step forward. Nor is it happenstance that the very large co-varies with the prolonged and the very small co-varies with the exceptionally brief and the emergent long axis need not necessarily be space, time, or even space-time.

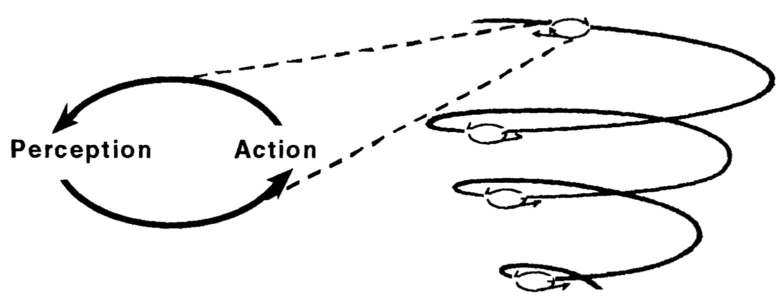

Figure 2.4. *Perception-Action Loops expand and interpolate into individual and collective Perception-Action Spirals*

2.2.5 Synthesizing Scales

We have suggested that there is a continual tension between these respective regions of perception and action, as humankind seeks to physically control that which they can perceive. If the ecological approach can be characterized as a looping of the perception-action cycle, what we have presented here represents an extension to this concept, seeing exploration more as a perception-action spiral. In this conception there is a continual expansion of the ranges over which the perception-action loop occurs, (see Figure 2.4). It is indeed the specific purpose of technology to synthesize the inequities in the envelopes of perception and action. Therefore, we can recognize a companion view of technology as the vehicle which brings *universalrange* to *humanrange* by representing entities at our level. We have not explored this form of mutuality here directly but recognize its validity.

However, in addition to the tension created by the dissonance between regions of perception and action, there is also a growing dissonance between actions and experience. If a human operator (or supervisory controller) interacts with a system via aided perceptions and aided actions, then the directness of everyday experience is, at present, replaced by a more abstract and indirect relationship between the person and the environment. This is particularly true for extensions beyond regions in which light magnification simply rescales the display. Such a difference is represented by the respective disparities in the Envelopes of Figure 2.1. This leads to our second observation:

2. The further the envelopes expand away from the relatively fixed region of human-range, the further divorced are actions from experience.

The corollary of this growing indirectness is that as we progress in our efforts to perceive and influence the very large and the very small, we have begun to rely progressively on metaphorical representations of these entities with which, by constraint, we have had no direct experience, although virtual reality promises a potential resolution for such dissociation as we discuss below. The advisability of this strategy and some potential remedies are the topics of other chapters in the present text. Thus technology must seek not only to expand *universalrange* but also to provide a representation of its content in a manner coherent with *humanrange*. This represents a major challenge to future development of technology in general, and to the discipline of human factors in particular.

As we explore ranges of our 'universe' that are further from our personal experience, we have traditionally dealt with progressively more interconnected and interactive systems (Perrow, 1984). Indeed, it is the emergent properties of these interactions which frequently provide the challenge, the uncertainty, and the novelty which is sought alongside the expansiveness of exploration. However, the problem mounts as we move further from *humanrange* and as we use progressively indeterminant prosthetics to do so. It is, of course, a step