FROM BRAINS TO BRANCH POINTS: COGNITIVE CONSTRAINTS IN NAVIGATIONAL DESIGN

by

Susanne Jul

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Computer Science and Engineering)
in The University of Michigan
2004

Doctoral Committee

Professor George W. Furnas, Chair
Professor Kimberlee Kearfott
Professor John Laird
George G. Robertson, Microsoft Research

For

Irma Wyman

Who showed the world the engineering capabilities of women,
and is now helping women to show them to themselves.

ACKNOWLEDGEMENTS

Un-slumping yourself
is not easily done.
Dr. Seuss, *Oh, the Places You'll Go!*[i]

Foremost,

Mom,

for all her support, and for making me a learning junkie.

- *Beth*, *Eric* and *Lisbeth*, for unquestioning understanding and love.
- *George Furnas*, for innumerable insights, intellectual support and unwavering friendship.
- *Sandy MacMahon*, my one and only dissertation buddy, for shared pain and euphoria, despite disciplinary differences.
- *Catherine Freemire*, for helping me to discover and appreciate the peculiarities that make me Me, and understand what it takes to make Me productive.
- *Irma Wyman*, for faith and financial support.
- *Maurita* (and *John*) *Holland*, for allowing me into their home, their heads and their hearts.
- *Polle Zellweger* and *Barry Peterson*, for unparalleled enthusiasm about my mission and unbridled comments on flaws in my writing.
- The *Naval Postgraduate School* (embodied by *Rudy Darken* and *Mike Zyda*), *Georgia Tech* (embodied by *Gregory Abowd*, *Jen Mankoff*, *Beth Mynatt* and *Blair MacIntyre*) and *IBM Almaden* (embodied by *Dan Russell*), for supplying physical facilities in the course of my migratory search for a Place in the Sun.

- *Jeff Shrager*, for shoring up my statistical ineptitude.
- *John Laird*, *Jim Hollan*, and *Mary Czerwinski*, for unfailing and unequivocal encouragement whenever our paths crossed.
- *Gayle Palmieri Daraio*, for immutable faith.
- *Starbucks* and *T-Mobile*, for affordable office space.

And last, but by no means least,
Hobben (in memoriam) and *Caithven*,
for 24/7 fuzz therapy.

---

[i] [242] Reprinted from *Oh, the Places You'll Go!*, Dr. Seuss, p. 19, ©1990, with permission from Random House Publications.

PREFACE

Considering the results of this research, there is a range of potential solutions to wayfinding problems. If mistakes are the product of high uncertainty and constraints on driver information processing, then solutions will have to reduce this uncertainty and minimize the constraints. Not much can realistically be done to change the road geometry or the driver …

Peter C. Burns[ii]

The world can doubtless never be well known by theory: practice is absolutely necessary; but surely it is of great use to a young man, before he sets out for that country, full of mazes, windings, and turnings, to have at least a general map of it, made by some experienced traveller.

Lord Chesterfield[iii]

Back when I was working as a user interface designer and engineer in the heart of Silicon Valley, trying to adhere to the principles of user-centered design. Secretly, however, I was always skeptical of the part where I was supposed to go forth and study users. Certainly, I believed in the value of understanding the users and of having first-hand knowledge of what they were trying to do and the problems they faced. But, seriously, I was going to learn more from studying six users for a week than thousands of psychology researchers had learned about humans from over a century of study? Clearly, I was spending most of my time "discovering" things that were already known.

Hence, I started this journey with a vague notion that there had to be a way to make all that delicious psychological knowledge available to designers without making them study all that psychology. (And better yet, maybe there was a way to put it into engineering tools so that they couldn't help but use it.) Little did I know how long, arduous and lonely the journey would be. Little did I know how thrilling the mazes, windings, and turnings I would find would be.

I started with navigation because "it's a simple, well-understood problem that has been studied extensively by psychologists." Ha! First, of course, there's nothing simple in

---

[ii] Burns, P. C. (1998). Wayfinding Errors While Driving. *Journal of Environmental Psychology*, Vol 18(2) Jun, 209-217.

[iii] Letter, 30 Aug. 1749, first published 1774; reprinted in *The Letters of the Earl of Chesterfield to His Son*, vol. 1, no. 190, ed. by Charles Strachey, 1901.

psychology. Second, as I had to learn by tramping all over environmental psychology, cognitive psychology, spatial cognition, and cognitive mapping, with brief forays into linguistics, robotics, and computational geometry, understanding something as a problem in psychology is vastly different from understanding it as a problem in design. Then, I had to realize that, in electronic environments, we *can* do something to change the road geometry. In fact, it's one of the easiest things in the world. In fact, it's so easy that we're not sure what "a road" *is*, and even less sure of how it can be changed. The only thing that we're really sure of is that we still can't change the driver. So the question is: what does a road look like and how do you fit the road it to a driver?

And this map is, I hope, the beginning of the answer. I have become an experienced traveller and have wandered in the countries of Psychology, Design and Navigation. I have explored only a small portion, in theory as well as in practice. I sketch out what I have seen as accurately as I can in the hopes that others may travel with greater ease.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

CHAPTER 1
Introduction

You have brains in your head.
You have feet in your shoes.
You can steer yourself
any direction you choose.
Dr. Seuss, *Oh, the Places You'll Go!*[iv]

Most people equate "navigation" with "maps" and, ofttimes, "compasses." Designers often equate "navigation" with "landmarks" and, sometimes, "cognitive maps" or "motion control." "Brains," "feet," "shoes," "choose" and "directions," however, might represent navigation equally well and may actually express its essence better: Navigation entails a "brain" choosing from different "directions" in which "feet" and "shoes" can go, and directing them to go there. In the course of this process, the "brain" may employ maps, compasses, landmarks and cognitive maps, and certainly must have some means of controlling "feet" and "shoes," but maps, compasses, landmarks, cognitive maps, feet and shoes are aids to particular ways of navigating rather than essential elements of the process itself. Most conceptions of navigation, however, agree that it is somehow related to the cognitive aspects of directing movement through an environment, and that navigation in different environments is fundamentally the same. This is true in physical as well as electronic environments, although movement is physical in the one and conceptual in the other.

The term *navigation* is used here to denote a complex of cognitive activities that is associated with the task of determining where places and things are, how to get to them and actually getting there. This entails determining what movement is necessary,

[iv] [242] Reprinted from *Oh, the Places You'll Go!*, Dr. Seuss, p. 4, ©1990, with permission from Random House Publications.

controlling movement and actually moving. Navigation is considered a *cognitive task*—a set of mental functions or behaviors to be performed, described in terms of the goals to be achieved by performing those functions—regardless of whether movement is physical or conceptual. The navigational task always serves the needs of some task or purpose other than navigating, i.e., people do not set out "to navigate," but rather have some superordinate goal, such as "to buy milk," "to see the sights," or even "to learn to navigate (by compass)." The spatial needs of this *superordinate task* engender the navigational task. Navigation is necessary in any environment of human endeavor where tasks require movement between two locations that cannot be perceived simultaneously, even if such movement is conceptual or metaphoric.

Human-computer interaction is an academic and professional discipline that seeks to understand, design and develop *user interfaces* to electronic environments—tools that allow people to direct the activities of computational devices, and electronic user interfaces to physical environments—electronic tools that allow people to perceive and manipulate properties of physical devices. The field also seeks to understand *usability*—how tools meet the needs of their users. Most electronic user interfaces are symbolic representations of complex environments and are themselves complex environments through which movement is required. Support for navigation is, consequently, an unavoidable and critical component of their design.

The field of human-computer interaction has expended considerable effort on understanding *navigational design* of electronic environments—design that affects navigation, including design of an environment, augmentation of an environment, and design of specialized aids to support navigational activity. These efforts range from developing specific navigational designs [16, 56, 78, 123, 157, 216, 257, 279], to conducting studies of navigational techniques [18, 50, 59, 253], to articulating design principles and guidelines for navigational design [81, 195, 275]. In spite of these efforts, navigation continues to be a common source of usability problems [54, 142, 195], which suggests that better support for navigational design may reduce product development cost.

The immediate goal of this dissertation is to develop a systematic understanding of navigation as a problem in design. The purpose is to help designers of electronic environments develop acceptable (as defined by the overall design goals) navigational designs more rapidly and more consistently. The work focuses specifically on the design of electronic environments for use by human navigators.

Design Knowledge vs. Psychological Knowledge

A key intuition underlying this work is that design knowledge differs from psychological knowledge, and that understanding navigation as a problem in design differs from understanding navigation as problem in psychology. Understanding navigation as a problem in psychology aims at explaining the cognitive structures and mechanisms that underlie navigational behavior. It may produce cognitive models that, given a particular task and navigational design, can be used to make predictions about behavior or performance.

Understanding navigation as a problem in design, in contrast, aims at describing the elements and properties of design that affect navigation and developing prescriptive models of the relationship between environmental features and navigational performance. In other words, the psychological perspective seeks to understand *how* humans navigate, whereas the design perspective seeks to understand *what* they need to do so. Providing designers with prescriptive models is expected to help them "predict" an appropriate navigational design, given a task and the desired navigational performance. Articulating design knowledge is expected to allow designers to acquire and use it earlier and more consistently in the design process, and provides a basis for developing predictive models.

A second intuition underlying the work is that much design knowledge can be derived from existing psychological knowledge. That is, in the course of developing an understanding of how people navigate, psychology reveals considerable information about what they need to do so. Extracting design knowledge from psychological knowledge is, however, not a simple task. The present work develops an understanding of what key design knowledge might be, proposes a heuristic process for extracting it from psychological knowledge and applies the process in the domain of navigational design of electronic environments.

Design and Design Knowledge

The assumption that design knowledge differs from psychological knowledge raises the question of what design is, what knowledge is important to it, how it may be acquired and what is already available.

Design

"A designer makes things. Sometimes he makes the final product; more often, he makes a representation—a plan, program or image—of an artifact to be constructed by others" [235, p. 78]. Design "tell[s] us how things ought to be" [160, p. 1]. The word "design" is used to denote both the process of imagining how things ought to be and the description or representation of how they might be, that is, it is used to denote process as well as product.

By extension, "design" is also used to refer to any seemingly systematic and purposeful arrangement—e.g., the "design" of a flower—regardless of whether it resulted from an intentional process. Note that many designs that result from an intentional process nonetheless result from serendipity and chance occurrence. For example, the "design" of a city may be as much the result of opportunistic development as of urban planning [2], while the "design" of a tree may be as much a result of intentional pruning and shaping as of natural development. No effort will be made to distinguish between intentional and naturally occurring "designs."[v]

[v] If this causes difficulty, the reader should assume a creationist view and envision a universal designer.

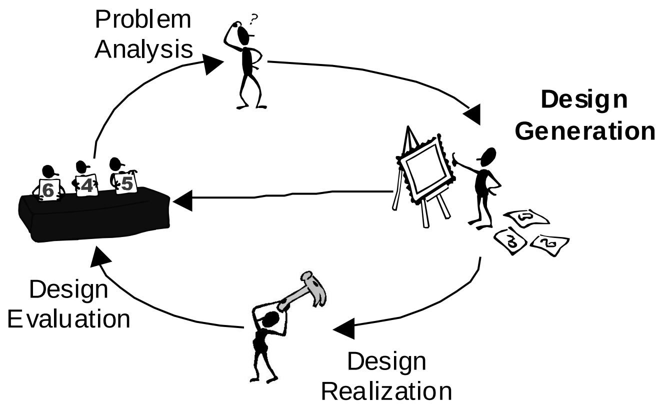


Figure 1 The iterative design cycle.

The Iterative Design Cycle

Cognitively, design is regarded as a problem-solving and decision-making process that comprises three phases characterized by different goals and different activities [14, 32, 94, 128, 161, 171, 252]. Problem analysis is aimed at understanding the problems a design should or is failing to address—what ought to be different. This phase is characterized by examination and exploration of the purposes the final design is intended to serve and the situation in which it is intended to be used. *Design generation* produces ideas, at varying levels of detail, of how those problems might be addressed—how things might be different. This phase is characterized by exploration of different possible problem solutions and different approaches to solving the problem. *Design evaluation* tests whether a proposed solution addresses or can be expected to address the problem satisfactorily—determining whether the proposed changes will result in things being how they ought to be. This phase is characterized by inspection and testing of proposed solutions and often involves simulation of their use.

Many who have studied design identify a fourth phase, *design realization*, in which a particular solution or an analogue thereof is made tangible [32, 94, 161, 171, 252]—making the idea produced in the generative phase a thing. This phase is characterized by consideration of technical difficulties associated with constructing the solution (or its analogue), and is optionally performed after design generation in preparation for design evaluation.

Design is an iterative process and a final design is usually the result of numerous iterations through these four phases (Figure 1) [14, 32, 161, 235]. Design realization may be omitted in some iterations, particularly in the early stages of design. If the proposed solution is not realized, it is nonetheless evaluated intuitively or through mental simulation [235, 272]. The iterative nature of the process reflects a fundamental reliance on trial and error to produce viable designs: See a problem, generate a possible solution, test it, try again, and repeat until an acceptable solution is found or resources are exhausted. Although this is a process of trial and error, it is not a random guessing process, but is rather systematic experimentation guided by the designer's experience and knowledge [235]. Reducing the number of iterations required to achieve an acceptable design is one way of helping designers meet design goals more rapidly and more consistently. One means of reducing the number of iterations is to reduce the amount of trial and error needed.

Trial and error can be reduced by improving problem analysis—helping designers recognize the "right" problems faster, or by improving design generation—helping designers generate "good" solutions sooner, or both. Either approach potentially reduces the number of *revolutionary* iterations (iterations that explore fundamentally different solutions) required or the number of *evolutionary* iterations (iterations that explore variations of a particular solution) devoted to poor alternatives. Unfruitful evolutionary iterations are a commonly recognized obstacle to design productivity: Designers tend to become fixated on particular designs—becoming enamored with certain ideas, as it were—and often spend many iterations perfecting fundamentally flawed solutions [14, 53, 224, 272]. Insidiously, the difficulty of discarding a particular solution increases as more iterations are devoted to it [14, 224, 272].

Design Constraints

Exactly how a designer recognizes the "right" problems, gets new ideas and generates "good" design alternatives is not well understood. However, many who have studied this question agree that knowledge of *design constraints*—limitations on what constitutes an acceptable solution—plays a critical role [9, 46, 52, 79, 94, 128, 161, 227, 252, 272]. Experienced designers seem to rely on an understanding, either explicit or implicit, of the constraints that are pertinent to a particular design situation [46, 52, 128, 161, 227, 252, 272]. A design constraint defines a relationship among different design elements or among properties of a single design element that determines the acceptability of a solution [161, 227]. For example, anatomy of the average adult human dictates that the dimensions for steps in a ladder or staircase should sum to 18 inches (vertical plus horizontal dimension, known as "rise" and "run," respectively), with a ratio of 7/11 inches being optimal. This constraint is known in architecture and building codes as the "7-11 rule."

Some design constraints are *variant*—applicable to some but not all designs of a particular type, while others are *invariant*—applicable to all designs of a particular type. For example, the number of staircases and their requisite heights may differ from building to building, but the rules for constructing staircases do not. Because variant constraints differ across design situations, only general knowledge of them can be captured and transferred in the absence of a specific situation, for instance, general strategies for placing and subdividing staircases. Knowledge of invariant constraints, however, can be identified and formulated in detail outside a specific situation, such as the 7-11 rule mentioned earlier.

Design is a process of determining which constraints are applicable to a particular situation and how they should be satisfied [161, 227, 235]. As more constraints are added and resolved, the problem that will be addressed becomes more clearly defined and the final design more specific. Designers use knowledge of constraints to direct their attention to key problem areas and to filter out immaterial issues during problem analysis [128], and to focus their attention on and direct manipulation of critical features [128, 227, 248] during design generation. Interestingly, in both cases, recognizing inappropriate and irrelevant constraints may be more critical to success than recognizing those that are relevant [128, 161, 227, 237]. Thus, the better the designer understands the constraints that do and do not apply to a particular type of design, the more likely they are to produce an acceptable design quickly.

Invariant constraints arise because of conditions that are independent of the design problem—human anatomy in the case of the 7-11 rule of staircase design. As there is a causal relationship between these conditions and the consequent invariant constraints, knowledge of the conditions provides a basis for inferring the invariant constraints. In the case of electronic environments, cognition is a primary source of invariant constraints, and knowledge of cognition provides a rich basis for identifying them. For the present work, it is assumed that knowledge of navigational design constraints can be derived from psychological knowledge of navigation. Chapter 2 offers a more detailed examination of the nature of design constraints.

Acquiring Knowledge of Design Constraints

Designers can acquire knowledge of invariant constraints either by direct experience or through training. Learning from direct experience is, unfortunately, a slow and uncertain process. Its success depends on the individual's ability to synthesize abstract concepts [105] and to recognize causal relationships [146] from examples, as well as on the number, variety and quality of the examples to which they chance to be exposed.

Not only may this process take years, but also, for the near future, the majority of available examples of navigational design will be set in physical environments. Accommodations to the laws of natural physics permeate physical designs to such an extent that it is difficult or even impossible to dissociate constraints dictated by physics from those dictated by cognition. Designs for electronic environments that are based solely on knowledge derived from experience with physical designs will likely resemble these. At best, such emulative designs fail to take advantage of the greater flexibility of electronic environments. At worst, they encourage misleading metaphors and induce erroneous mental models [197].

Learning about invariant constraints through training depends on their already being known, either implicitly, by someone else (e.g., in a mentoring situation) or explicitly, in a systematic articulation (e.g., in a formal training situation that depends on textbooks). The former, in turn, depends on someone else having acquired the knowledge through training or by experience. In either case, a body of systematically articulated constraints is likely to speed the learning process.

Existing Knowledge of Navigational Design Constraints

A considerable amount of psychological knowledge about navigational cognition and behavior is available, including descriptions of cognitive processes involved in navigation [31, 48, 211, 256], cognitive mechanisms underlying these processes [67, 89, 97], and the effect of various environmental characteristics on navigational behavior [58, 59, 109, 168, 205]. Study of underlying cognitive mechanisms, in particular, has been quite extensive, and systematic articulations of their functioning and development are available [51, 64, 107, 245]. However, these all represent psychological knowledge, and none constitutes design knowledge. No systematic articulation of the constraints navigational cognition imposes on navigational design exists, and designers, at present, must acquire knowledge of them through direct or second-hand experience [35].

The reformulated goal of the present work is to articulate a set of invariant constraints on navigational design imposed by navigational cognition. This goal is grounded in the assumption that knowledge of design constraints is critical to the analytical and generative phases of design, and that providing designers with such knowledge can be expected to help them produce good designs faster and more consistently.

A Process for Developing Design Knowledge

The work assumes that the relationship between cognitive tasks and environmental design is a key source of constraints in the design of electronic environments. Based on this assumption, the dissertation offers a process for developing design knowledge from psychological knowledge and applies it to developing an understanding of navigation as a problem in design. The basic *design knowledge development* process comprises four

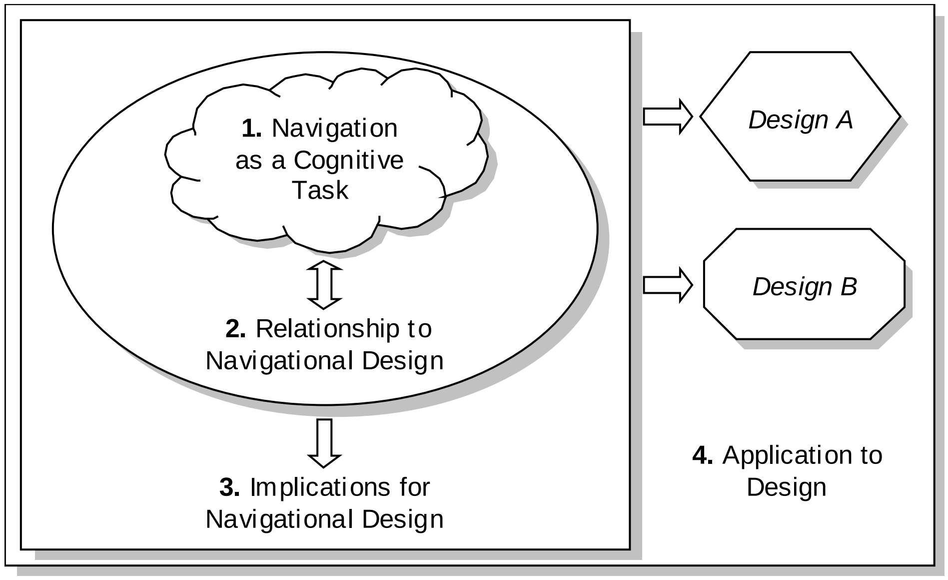


Figure 2 Design knowledge development process applied to understanding navigation as a problem in design.

steps. Figure 2 shows how it is applied to the cognitive task of navigation: First, using psychological evidence, develop an understanding of navigation as cognitive task. Second, develop an understanding of the relationships between the cognitive task of navigation and the elements of navigational design, also using psychological evidence. Third, articulate the implications for design—the design constraints—of those relationships. Fourth, describe how those implications may be applied in actual design situations.

Step 1: Understanding Navigation as a Cognitive Task

A “cognitive task” is here regarded as a set of mental functions or behaviors to be performed, described in terms of the goals to be achieved by performing those functions. The goals that must be achieved in order to navigate could be identified theoretically by analyzing the problems navigation poses. This approach would result in a description of ideal behavior. However, the intention of the present work is to support actual behavior. Actual behavior often differs from ideal behavior due to limitations not fully understood (e.g., limitations on human memory), or because it must meet the needs of many goals simultaneously. A complete theory of navigational behavior would account for differences between ideal and actual behavior, however, for the present purposes, a description of actual behavior is sufficient. The approach used here is to develop a description of the cognitive task of navigation from analysis of empirical evidence.

Analyzing empirical evidence to identify cognitive tasks reflects the assumption that cognitive goals may be inferred from observed behavior [184]. A cognitive goal may be achieved through a variety of behaviors, e.g., two numbers may be added by counting on one's fingers, by asking someone else for the answer, or by using a calculator. Conversely, a behavior may be employed in achieving a variety of goals. For example, counting on one's fingers may be used to add two numbers, determine the day of the week or communicate one's age.

By examining the behaviors associated with navigation and the relationships among them, the cognitive goals these behaviors accomplish (and the relationships among them) may be surmised. These goals can then be used to describe the cognitive tasks of navigation. Although this approach imposes considerable effort (as shall be seen), it increases the likelihood that the identified design constraints will be germane to actual designs. Chapter 2 offers a more detailed examination of the relationships between behavior, cognition and design constraints.

Note that, as the aim of the work is to support the development of novel environments, it is important to distinguish between behaviors, or aspects of behavior, that result from the dictates of a particular environment and those that are fundamental to navigational cognition. For example, the goal of discriminating between "right" and "left" is induced by properties of a Euclidean spatial environment (or one that employs Euclidean metaphors), whereas discriminating between "here" and "there" is fundamental to navigation in any environment.

Step 2: Understanding the Relationships between Navigation and Navigational Design

Analysis of navigation as a cognitive task links cognitive tasks of navigation and cognitive behaviors. Considerable empirical evidence is available about relationships between cognitive behaviors and environmental phenomena in the context of navigation.

It is thus possible to identify relationships between the cognitive tasks of navigation and environmental phenomena. Unfortunately, because the empirical evidence was gathered to develop psychological knowledge (and is organized as such), it focuses on cognitive phenomena rather than features of navigational design. Meticulous analysis is required to draw out the latter, and entails developing a characterization of what environmental phenomena are features of navigational design.

Step 3: Understanding the Implications for Design

Describing the relationships between the cognitive tasks of navigation and navigational design reveals the constraints that cognition imposes on design—information that is useful to design. However, these constraints must still be articulated in the form of design knowledge, that is, be made explicit in a form that is directly accessible to designers. The constraints are here presented in the form of design principles that relate specific manipulations of design elements to effects on navigational performance.

Step 4: Application to Design

No understanding of a design problem can be said to be complete if it does not include an indication of how that understanding applies to practice. Satisfaction of the constraints revealed by the psychological evidence suggests a specific design process of analyzing the navigational needs imposed by the purpose or task the design is intended to serve, developing an initial design based on those needs and then applying the design principles to refine the design.

Applying the design knowledge development Process: From Brains to Branch Points

The work is structured around the design knowledge development process (Figure 2). It is divided into three parts. The first part, developed in Chapter 2, begins to address

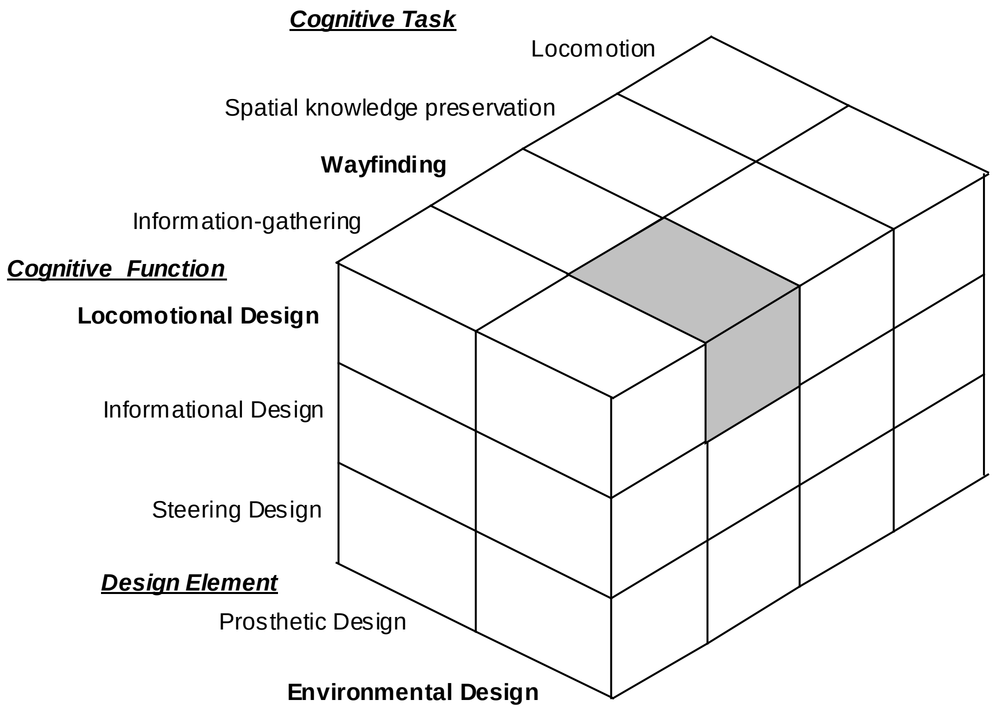
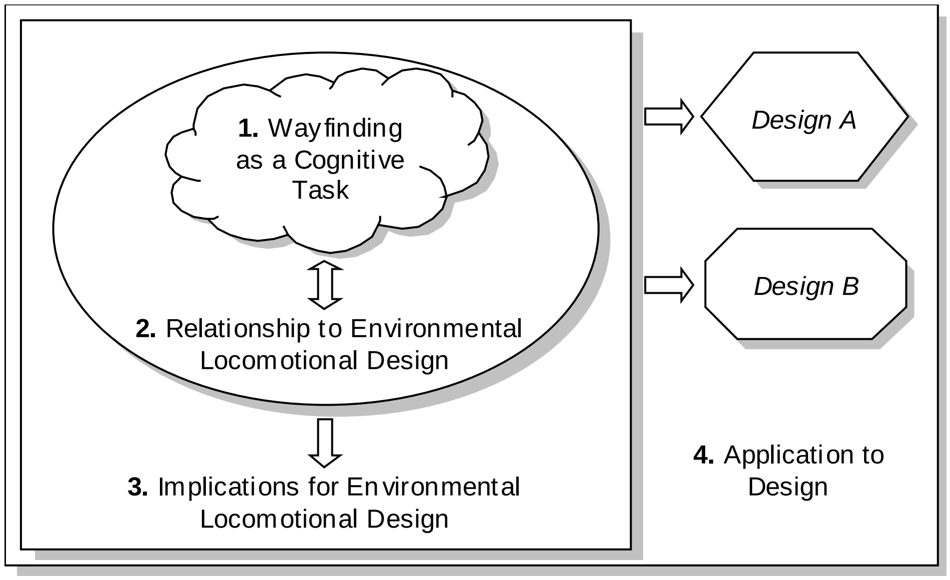


Figure 3 Decomposing the navigational design problem.

the problem of understanding navigation as a problem in design by analyzing the existing psychological literature to develop a general understanding of navigation as a cognitive task (step 1) and a general understanding of the relationships between navigation and navigational design (step 2). This results in a *design-oriented model of navigation* that decomposes the cognitive task of navigation into a set of four cognitive subtasks. It also yields a *taxonomy of navigational design* that comprises six subdomains. As each of the six subdomains potentially affects any of the four subtasks, the problem of understanding navigation as a problem in design can be decomposed into twenty-four subproblems (Figure 3).

Recognizing that addressing all twenty-four subproblems simultaneously is beyond the scope of this dissertation, the remainder of the work focuses on one subproblem. Thus, the second part of the work applies the design knowledge development process to understanding wayfinding as a problem in environmental locomotional design (s).



The process is identical to that of understanding navigation as a problem in design (Figure 2, p. 10), but the focus of each step has been narrowed.v

Figure 4 Design knowledge development process applied to understanding wayfinding as a problem in environmental locomotional design.

The first two steps—developing an understanding of wayfinding as a cognitive task and describing its relationships to environmental locomotional design—are laid out in Chapter 3. These two steps are accomplished through analysis of existing psychological evidence (as they were when they were applied to understanding of navigation in the first part of the work). The second step begins the synthesis of design knowledge by identifying specific elements of environmental locomotional design that are key to wayfinding cognition, and determining how design conceptualizations of some of these differs from their psychological conceptualizations.

The third step—describing the implications for design of the relationships identified in the second step—represents the true synthesis of design knowledge, in that it articulates specific design constraints. It is laid out in Chapter 4, along with the fourth step—detailing how the design constraints apply to design. Finally, the third part of the work, contained in Chapter 5, seeks to evaluate the success of the research through empirical evaluation.

Part 1: Understanding Navigation as a Problem in Design (Chapter 2)

Step 1: Understanding Navigation as a Cognitive Task (Chapter 2)

Cognitively, navigation can be viewed as a process of solving spatial problems and making decisions for the purposes of directing movement. This process entails actual (physical or conceptual) movement and may entail preservation of knowledge such as information used, solutions developed or decisions made. The analysis of the empirical evidence of the cognitive behaviors of navigation conducted in Chapter 3 yields a *Design-Oriented Model of Wayfinding* that comprises four major subtasks. *Locomotion* is the task of directing and controlling movement undertaken for the purpose of moving between distinct locations. *Wayfinding* is the spatial[vi] problem-solving and decision-making entailed in determining where to go and how to get there. *Spatial knowledge preservation* is the task of encoding and storing spatial knowledge for future need, as well as recalling and decoding such preserved knowledge. *Information-gathering* is the process of collecting information about the environment, such as where places and things are and how they are related spatially.

The four subtasks are not independent of each other. Wayfinding dictates what locomotional tasks must be undertaken [67, 214], while spatial knowledge is preserved in order to aid future wayfinding tasks [64, 140, 245] (although it may also serve non-navigational purposes). Information-gathering serves the needs of wayfinding and spatial knowledge preservation. Thus, wayfinding and spatial knowledge preservation can be regarded as the central tasks of navigation.

Preserving spatial knowledge is particularly useful and important in environments, such as the physical world, that are relatively stable, have a high or constant cost of information-gathering, in which the same portions are navigated repeatedly and in which getting lost potentially carries a high cost. Electronic environments, because of their

---

[vi] Note that “spatial” is used in its broadest sense of “having the nature of space” [6]. E.g., the sequence “a, b, c” is not spatial in the Euclidean sense of space, but defines an ordering that is spatial in nature (“a” is *before* “b”).

computational nature, may change radically and quickly, can aid information-gathering—even adapting to the needs of a specific navigator and a specific navigational task, are often used ephemerally, and, typically, being lost does not put the navigator in actual danger or require great effort to remedy. However, most efforts to design support for navigation in electronic environments have focused on facilitating spatial knowledge preservation rather than wayfinding, and few efforts have sought to understand how the properties of electronic environments might be used to change the cognitive demands of wayfinding.

Step 2: Relationships between Navigation and Navigational Design (Chapter 2)

The analysis of cognitive tasks suggests decomposing design according to *cognitive function*—the role a design or design element plays in the performance of a cognitive task. This yields three subdomains of navigational design. *Steering design* is the design of the relationship between human action and movement, and of tools to control movement. *Locomotional design* is the design of what movement is possible, including means of effecting movement. *Informational design* is the design of what information is available to the navigator through direct perception.

Each of these subdomains affects the performance of at least one of the cognitive subtasks and may affect several. Steering design determines what cognitive resources are required by the locomotion subtask. Locomotional design determines what problems wayfinding cognition must solve and how complex they are, and how complex spatial knowledge is. Informational design determines what information-gathering strategies are useful and how successful they can be. However, informational design also partially determines what information is available to wayfinding and spatial knowledge preservation. Informational and locomotional designs conspire to determine, in part, where information is available for information-gathering. Steering design, alone among the three subdomains, affects only one subtask directly.

The nature of navigational design suggests decomposition according to the type of elements that are manipulated. *Environmental design* manipulates properties of the environment itself, whereas *prosthetic design* manipulates properties of aids that allow the navigator to detect or make use of environmental properties. For example, bridges and roads change the environment, while maps and compasses allow the navigator to take advantage of environmental properties (the stability of an environment and the earth's electromagnetic field, respectively). Both environmental and prosthetic design can affect all four cognitive subtasks.

Examination of the literature on the design of electronic environments shows that prosthetic design has received substantially more attention than environmental design, and that environmental steering design and environmental locomotional design have been particularly neglected. While this distribution of effort reflects the needs of navigational design in the physical world, it reveals a failure to explore design opportunities offered by electronic environments, especially, opportunities stemming from the combination of their computational nature and freedom from the laws of natural physics. Environmental design determines, in part, the need for and benefit of prosthetic design, and evidence from the physical world indicates that locomotional design has greater influence on wayfinding performance than informational design [204]. While locomotional design is costly to manipulate in the physical world, it is easily manipulated in electronic environments.

These two decompositions—by cognitive function and by design elements—are orthogonal to each other, resulting in a taxonomy of navigational design comprising six subdomains. These subdomains potentially affect each of the four cognitive subtasks, resulting in twenty-four possible subproblems of navigational design (Figure 3), corresponding to twenty-four possible sets of constraints to be explored. Eventually, these distinct sets must be integrated and suggestions for resolving conflicts developed. However, before integration can be addressed, one set must be articulated and its utility to design determined. This dissertation attempts to articulate a set of constraints imposed by the cognitive task of wayfinding on environmental locomotional design. This set was selected because wayfinding is fundamental to navigation and has been somewhat neglected in design efforts, and because environmental locomotional design is fundamental in defining the problems wayfinding must address.

Part 2: Understanding Wayfinding as a Problem in Environmental Locomotional Design (Chapter 3, Chapter 4)

The second part of the work applies the design knowledge development process to the problem of understanding wayfinding as a problem in environmental locomotional design (Figure 4). The first two steps represent a detailed analysis of psychological knowledge of wayfinding cognition and its relationship to environmental locomotional design, and the second two steps are a synthesis of this knowledge into design knowledge.

Step 1: Understanding Wayfinding as a Cognitive Task (Chapter 3)

The first part of the analysis confirms the commonly offered assumption that wayfinding conforms to models of general problem-solving and decision-making behavior by examining three models of general problem-solving and decision-making behavior, and comparing them to empirical evidence regarding wayfinding behavior. It then maps the wayfinding behaviors described in the literature onto a generic model of general problem-solving and decision-making behavior, resulting in a *Design-Oriented Model of Wayfinding* as a cognitive task comprising four subtasks. *Path-identification* is the task of understanding of the status, attributes, and dynamics of locations and paths in the environment. *Route-prediction* is the task of predicting which locations might be destinations, and which paths might represent routes to the desired destination. *Route-selection* is the task of selecting which of a set of possible paths to take. *Route-following* is the task of matching environmental and conceptual features to ensure that movement follows the selected path and route. Wayfinding is an iterative cumulative process that requires completion of all four subtasks.

Step 2: Understanding the Relationships between Wayfinding and Environmental Locomotional Design (Chapter 3)

Guided by the Design-Oriented Model of Wayfinding, the psychological evidence is then analyzed further to identify what elements and properties of environmental locomotional design are critical to wayfinding behavior and how they affect wayfinding performance. This examination yields four critical elements. The first element is the *locomotional structure*—a set of interconnected locations and paths—offered by the environment. It defines the wayfinding problems that are posed by that environment. Its complexity and organization determines the quantity and complexity of reasoning required to solve these problems.

The second element is the relationship between the superordinate task and the locomotional structure available to the wayfinder. The superordinate task defines a set of destinations and routes that are necessary to its completion—the *task-defined structure.* How similar the environmental and task-defined structures are determines whether the wayfinding task can be accomplished and how much overhead it introduces.

The third element is the spatial and temporal placement of *information access regions*—sets of contiguous locations at which specific information is perceptually available. Information access regions are an emergent property of the relationship the locomotional structure, the *perceptual structure*—e.g., a system of sight lines—and informational design, so are only, in part, elements of environmental locomotional design. The temporal placement of information access regions is a function of the relationship between movement and key locations in the locomotional structure.

Finally, the relationship between steering design and the locomotional structure affects the complexity of remaining within a particular locomotional structure. This relationship is only a factor in environments where deviation from the locomotional structure is possible, e.g., in the physical world, a car may go off the road, whereas in hypertext movement cannot “go off the link.”

Step 3: Understanding the Implications for Design (Chapter 4)

The third step synthesizes the psychological knowledge analyzed in the second step into design knowledge, by reformulating the relationships identified between wayfinding and environmental locomotional design as a set of twelve design principles. These principles link specific manipulations of design elements to their potential effects on wayfinding performance. While the underlying psychological motivation is provided along with each principle, this psychological knowledge is not available explicitly from the principles themselves. This reflects the abstraction that occurs in any synthetic process.

Step 4: Application to Design (Chapter 4)

The fourth step completes the design knowledge development process by demonstrating the application of the design principles to actual design. As each principle is developed (as part of the third step), it is illustrated in a running design example that develops a design for everyday file system interaction in a conventional desktop environment. Pursuant to an initial task analysis, the actual design developed, the *Repeat File Access* design, focuses on facilitating access to files that the user has accessed previously. The design is developed along with the principles, so the start of the fourth step coincides with the start of the third step.

The experience of developing the Repeat File Access design suggests a *Locomotional Design Process* comprising five steps. The first four steps are: identification of the navigational design goals, identification of the task-defined structure, generation of one or more initial designs, and refinement of the initial designs by application of the design principles. Note that the first two steps support the problem analysis phase of design, while the third and fourth support design generation. An optional fifth step then reapplies the principles to increase the complexity of wayfinding in the design. This step recognizes that the simplest possible design does not always meet design requirements. E.g., in the design of interactive games and in many learning situations, design requirements call for making interaction more complex than ostensibly necessary.

The Locomotional Design Process is then employed in and illustrated by a second design example that seeks to explore ways of providing general navigational support in a novel environment—spatial multiscale. This exercise yields two designs, the *Voronoi-based* design, which emerges from consideration of basic properties of the task and environment, and the *cluster-based* design, which focuses on more advanced and more conventional properties. The latter is a more conventional design that is suitable for a narrower range of tasks. It conforms to the initial set of design principles.

The Voronoi-based design is more novel and is suitable for a broader range of tasks, but appears to violate two of the twelve design principles. Nonetheless, the design seems promising. As this promise is confirmed in an empirical study in the third part of the work (*Part 3: Research Evaluation*, p. 21), the discrepancies are examined in detail. This results in three additional design principles that are hypothesized to account for the apparent contradictions. These three principles do not contradict existing psychological evidence, but rather speculate about potential interactions between design attributes that do not appear to have been studied yet.

Part 3: Research Evaluation (Chapter 5)

Rigorous scientific evaluation of research is always difficult, but is nearly impossible in applied disciplines, such as design. In such fields, the concepts of interest are often abstract and can only be operationalized imperfectly. For example, the concept of usability, which is at the heart of most efforts in human-computer interaction, is frequently measured in terms of “time on task” and “user satisfaction.” The former is quantitative and is easily measured, but does not provide any indication, for example, of how well the task was performed. The latter, conversely, is a qualitative measure that is either subjective or which must itself be operationalized. Further, operational variables may be influenced by a number of factors that cannot, in practice, be isolated or, in some cases, even identified in advance. For example, “time on task” and “user satisfaction” measures might both be affected by such factors as what a subject had for dinner the night before, or network problems that cause system response time to vary more than normally.

An additional obstacle to evaluating design research is that the success of a design—an abstract idea—can only be measured via some realization of that design—an actual artifact. The realization process—implementation in the case of electronic environments—often introduces a plethora of factors that affect the success of the design, but which are not an integral part of the design. These factors may represent attributes not specified by the design, or compromises made during realization. For instance, menu options in a software application must necessarily be presented using a particular background color and font, yet these may not have been specified in a design for menu interaction, or, if they were, the specified color and font may not be available and substitutions made. A poor choice of either might impair menu use and prevent measurement of the usability of the underlying menu interaction design.

In spite of these obstacles, some effort must be made to evaluate the present work. Ultimately, the property that is to be measured is the effectiveness of the proposed design principles to design. (Although the psychological validity of the principles may be of interest to psychology, it is their utility that is of importance to design.) “Effectiveness to design,” however, compounds three distinct properties: the usability of the designs that are produced, the efficiency with which they can be produced and the reliability of their production. The first is a property of realizations of design products, and the latter two are properties of the design process. Evaluation of whether the overall goal of the work has been achieved thus requires two units of analysis: design process and design product.

Evaluating the effect of providing designers with knowledge of the design principles on the efficiency and reliability of the design process is, if anything, more complex than measuring usability of actual designs. It entails communicating the principles to other designers, observing them applying the principles in a variety of design situations and evaluating the usability of the resulting designs. Communicating the principles to others, in turn, entails developing and testing a communication process that guarantees that recipients understand the principles and their application correctly and minimizes misconceptions introduced by the communication itself. Designers must then be observed carefully (or matched with control groups) to ensure that the design knowledge provided indeed influenced their designs or design processes. Finally, the resulting designs must be subject to some form of testing to ascertain how well they meet the intended design goals.

Initial subjects for such evaluation of the present work would be user interface designers of some experience and competence. In order provide a satisfying experience that does not leave participants with large bodies of unanswered questions, the design knowledge provided would have to be “complete,” that is, it would have to sustain them throughout a “normal” design effort. The set of design principles developed here covers only environmental locomotional design. An normal design effort must also address informational design. Thus, "complete" design knowledge would have to include a set of principles for environmental informational design in service of wayfinding. Developing such principles is beyond the scope of the present work.

Proper evaluation of the effect of the design principles on design process is thus a major and separate effort, and is beyond the scope of the present work. Evidence that the principles can be expected to have the anticipated salutary effect on the design process rests on the persuasiveness of their derivation and the clarity of the development of the design examples provided, but actual evaluation is deferred to future work.

Evaluating the effect of application of the principles on individual designs is, however, within the present scope, at least to limited extent. One of the example designs—the Voronoi-based design for supporting navigation in spatial multiscale—was partially[vii] implemented and subject to user testing. Results comparing the "informed" design to a conventional design for movement in this type of environment yielded an average reduction in time on task of 30% on a directed search task (moving between specified locations in a given sequence). This was accompanied by reductions in measures of effort, such as mouse movement, of up to 84%, and a significant increase in reported user satisfaction. Overall, the data imply that the design manipulations suggested by the design principles reduced the cognitive overhead of wayfinding, as anticipated. The experimental design and results are described in Chapter 5.

Contributions

Contributions of this dissertation result from the application of each of the four steps of the design knowledge development process (Figure 2, Figure 4) as well as the exploration of the process itself. They span four levels of abstraction, ranging from the actual designs produced to an increased understanding of the distinct needs of human-computer interaction as a design discipline.

[vii] The implementation omits portions of the design resulting from consideration of two of the fifteen principles in order to prevent confounding factors.

At the first level of abstraction, that of actual design, the work offers three detailed designs—two for a multiscale and one for a desktop environment—that may be used as presented or that may serve to inspire other designs. These designs support movement in significantly different environments, but have enough commonality to be generalized as a single technique, *Predictive Targeted Movement* [136]. This is a general technique for designing locomotional support for directed search tasks wherein a minimum of wayfinding overhead is desired. The implementation and testing of the multiscale design resulted in two software frameworks: one to manage the concepts and interactions required by the design, and one to collect and process user interaction data. Both are available for public use [114].

At the second level of abstraction, that of understanding the implications of wayfinding for environmental locomotional design, the work offers a set of design principles that link wayfinding performance to specific elements of environmental locomotional design. These principles may help designers during design problem analysis to recognize which navigational needs should be addressed and which are not being met. They can be applied directly during design generation to suggest design alternatives that meet the required needs while avoiding common navigational usability problems. Both uses are expected to reduce the amount of trial and error necessary to achieving satisfactory navigational designs, and consequently improve the efficiency and reliability of the design process.

At the third level of abstraction, that of understanding navigation, navigational design and the relationship between them, the work offers two conceptual frameworks. The first framework, a design-oriented model of navigation, draws together an extensive and diffuse body of literature, and provides a structure for its organization. It also serves to place disjointed research and design efforts in perspective. This model differs from some previously proposed models [67, 256] in that it is based on empirical evidence of navigational behavior rather than on theoretical consideration of ideal behavior. It differs from most psychology-oriented models [31, 48, 67, 256] by explicitly seeking to represent fundamental cognitive behavior and to discount behaviors resulting from the dictates of a particular environment. The second framework, a taxonomy of navigational design, organizes a different body of literature and provides a structure for characterizing navigational design efforts.

Both frameworks encourage designers and researchers to consider different aspects of navigational cognition that need to be supported along with different aspects of design that can be manipulated to support them. They can be used to determine which aspects a particular design addresses or should address, as well as to suggest ways in which it might be extended to address other aspects.

At this level of abstraction, the work also offers the Design-Oriented Model of Wayfinding as a cognitive task. This model is based on careful consideration of three accepted models of general problem-solving and decision-making and provides firm grounding for the common assumption that wayfinding is a problem-solving and decision-making task. It allows research on general problem-solving and decision-making to be brought to bear on understanding wayfinding. The value of the model is demonstrated in its use to guide a detailed survey of the literature regarding the relationship between wayfinding and environmental locomotional design. This survey not only reveals the key elements of environmental locomotional design that affect wayfinding, but also identifies several psychological questions that have not yet been examined (cf. *APPENDIX D Open Psychological Questions*, p. 301).

Finally, at the fourth level of abstraction, that of supporting design, the work offers a detailed example of one specific type of design knowledge—knowledge of invariant design constraints—that may aid designers during problem analysis and design generation. This example demonstrates several ways in which design knowledge differs from psychological knowledge. These include a need to detail the potential effects of a range of possible design manipulations on task performance, rather than a need to explain the causes—e.g., cognitive mechanism—underlying such effects. They also include a need to describe, in detail, the complexity of environmental elements that appear to be simple psychologically.

At this level of abstraction, the work also proposes the design knowledge development process for developing design knowledge from information already available and documented by other disciplines—principally psychology, and offers a case

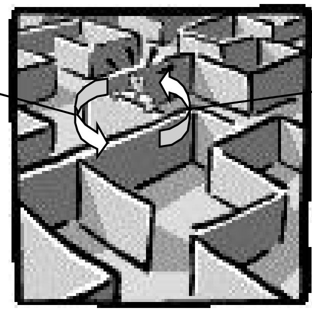


Figure 5 Different perspectives on using knowledge of the relationship between cognition and environment.

study of its application. The design knowledge development process seeks to identify and organize knowledge about a specific type of design problem. It is analogous to the software engineering process of Domain Analysis [8, 9, 223], but analyzes psychological rather than application domains. It represents the beginnings of an effort to develop software engineering techniques and tools that aid in addressing high-level cognitive issues in end products.

Conclusions

While the work described in this dissertation is neither conclusive nor concluded, it demonstrates that the knowledge necessary to user interface design differs from knowledge of cognition. It shows that the emphasis of the former must be on the relationship between cognitive performance and environmental phenomena, whereas the latter emphasizes cognitive behavior and mechanism. In other words, design must understand how the "feet in your shoes" and the "directions you choose" are related, while psychology primarily seeks to understand the "brains in your head."

It also demonstrates that much, but not all, of the necessary design knowledge can be extracted from existing psychological knowledge, and proposes a process for doing so. This process is heuristic and very general in nature, but offers a systematic guide for organizing and making sense of psychological knowledge in light of the needs of design. The process inverts the use of empirical psychological evidence: Traditionally, it is used to make inferences about the cognitive processes and mechanisms that have evolved in response to the demands of the external environment—a psychological perspective. The present use reverses the direction of inferencing and uses the same evidence to understand how to design the external environment to meet the needs of the cognitive mechanisms and tasks that have evolved—a design perspective (Figure 5).

Finally, the work illustrates how an emphasis on the needs of fundamental cognition can lead to consideration of different cognitive needs and different design approaches. Most prior efforts to support navigational design have focused on informational design, even in the design of electronic environments. The analysis of navigation as a cognitive task conducted here shows that the locomotional design controls demands for the informational design, and that the cognitive task can be managed through manipulations at the locomotional level of design.

These insights and many of the design principles may seem readily apparent from common sense and general human-computer interaction design principles. This obviousness may be deceptive, however: While the principles may be intuitively obvious individually, they are rarely observed in design collectively. Moreover, while the relationships among “brains,” “feet,” “shoes” and “choose” might seem straightforward, relationships between performance and environmental design might not be as plain to see in design domains supporting more complex cognitive tasks.

CHAPTER 2
Related Work

"In the places I go there are things that I see
"That I never could spell if I stopped with the Z.
"I'm telling you this 'cause you're one of my friends.
*"*My *alphabet starts where* your *alphabet ends!*
Dr. Seuss, *ON BEYOND ZEBRA!*[viii]

Just as some spelling tasks require new alphabetic letters, some understanding tasks require new concepts and vocabulary to describe them. Understanding navigation as a problem in design is such a task. Before adding to the plethora of concepts and vocabulary surrounding design and navigation, however, it is helpful to examine existing concepts and vocabulary to understand their utility as well as their deficiencies. This examination is aimed at understanding what knowledge might be useful to designers, what navigational cognition implies and what navigational design implies. It reveals useful existing concepts and vocabulary—"your alphabet"—as well as areas where new concepts and vocabularies are needed—"my alphabet."

The first concepts to be examined are those of the cognition of design. As described in Chapter 1, the goal of understanding navigation as a problem in design is motivated by a desire to help designers develop acceptable navigational designs more rapidly and more consistently. The present work seeks to make navigational design knowledge explicit so that it is more readily available to designers. This approach invites an examination of what knowledge designers use—in particular, the nature of problem-specific knowledge.

[viii] [239] Reprinted from *ON BEYOND ZEBRA!*, Dr. Seuss, p. 7, ©1955, with permission from Random House Publications.

An examination of studies of design problem-solving reveals that knowledge of invariant design constraints—limitations on what constitutes a solution that are shared by multiple design problems—plays a critical role. It also suggests that providing explicit knowledge of certain types of constraints may help designers recognize key features of design problems and suggest ways of addressing them. The examination is concluded with a review of how knowledge of invariant design constraints has been used to support design of user interfaces.

The second concept to be investigated is that of navigation as a cognitive task. Navigation and the cognition associated with navigation have been studied from a variety of perspectives, the results of which have been reported in an extensive and diverse body of literature. The analysis of this literature offered here yields a design-oriented model of navigation that decomposes navigation into four distinct cognitive subtasks that present differing challenges to design. This model differs in critical ways from the psychology-oriented model that is often assumed—explicitly or implicitly—in the design literature.

The third concept to be scrutinized is that of navigational design. This yields two dimensions for characterizing design features: according to the needs met (Cognitive Function), and according to the means by which they are met (Design Element). The two dimensions are orthogonal, defining a taxonomy of navigational design that comprises six subdomains. Although the taxonomy is based on theoretical considerations, a brief examination of the literature on navigational design of electronic environments reveals divisions corresponding to its categories. This examination demonstrates that the majority of reported design efforts address a single subdomain, and that most could readily be enhanced or extended by consideration of the demands of other subdomains.

These examinations of concepts yield new concepts and vocabulary for describing design, navigation and navigational design, implying that new understanding has been achieved. This new understanding is then used to shed light on prior efforts to support navigational design and relate them to the present work. This shows that most other efforts have focused on one step of the design knowledge development process and have not sought to develop a comprehensive understanding of navigation as a problem in design. Two notable exceptions have both focused on architectural design and neither goes beyond the assumptions that characterize the physical world.

Design Cognition, Knowledge and Constraints

The cognitive process of design is universally regarded as a form of problem-solving. This assumption is borne out by studies of design [14, 46, 52, 94, 163, 235, 272] and of problem-solving [100, 227, 248]. Most design problems are categorized as so-called "wicked" [228] or "ill-structured" [248] problems. Design problems notoriously exhibit two characteristics of wicked problems: (1) that the problem cannot be stated comprehensively and (2) that many possible solutions are possible [14, 46, 95, 161, 227, 252, 248].

Empirical studies show that prior knowledge plays an important role in solving such problems, particularly knowledge of similar problems and elements of their solutions [46, 52, 94, 100, 235, 272]. For instance, an architect might use knowledge of standard floorplans, typical room sizes, and elevation drawings [46], an industrial designer might use knowledge of material properties and mechanical assemblies [52], and a mechanical designer might use knowledge of flows of material, energy and electronic signals [272] in understanding and solving design problems in their respective domains.

The process of design problem-solving can be described as a process of identifying, imposing, and removing *design constraints*—limitations that determine what constitutes an acceptable solution. For example, the nature of the music to be performed in a concert hall constrains its size—rock music would deafen both musicians and audience in a small recital hall intended for chamber music, while early music played on period instruments would be inaudible to most in an outdoor amphitheatre venue intended for rock concerts. Constraints limit and prioritize the subproblems that must be addressed (e.g., regardless of the type of music to be played, acoustical considerations are of paramount importance in designing a concert hall) [46, 128, 227, 235], suggest important characteristics of design elements or relationships among them (e.g., audience seating, by today's conventions, must face the musicians) [128, 161, 227], and provide criteria against which solutions can be evaluated (e.g., seating accommodations must be sufficient to generate the desired revenues) [46, 128, 272].

Some constraints are dictated by initial design requirements (e.g., the physics of acoustics in the design of a concert hall), while others are imposed or discovered in the course of the design process (e.g., the decision to use continental seating[ix]) [128, 94, 161, 227, 235, 272]. Regardless of when a constraint is introduced into design deliberations, prior knowledge of it or similar constraints speeds its recognition and recognition of its significance [46, 100, 128, 161, 235, 272]. Knowledge of constraints that commonly apply to a design domain is an essential component of expert knowledge [46, 52, 100, 128, 161, 227, 235, 252, 248, 272]. Knowledge of specialized constraints of the problem domain particularly aids the speed and quality of design (hence the need to employ highly paid acoustical designers) [52, 100,161, 171, 235]. Possession of knowledge of general and domain-specific constraints is generally accepted to be an indicator of expertise [146, 161, 235, 250].

In the problem analysis phase of design, understanding of typical problems and the relationships among them (their interdependencies, relative importance, etc.) embodies knowledge of typical or potentially significant constraints. Such knowledge appears to help designers recognize typical and atypical problems and compensate for missing information in the problem statement [95, 248], and to determine the significance (or lack thereof) of seemingly related (or unrelated) problems [128]. For example, an experienced symphony hall designer understands that the attire of the audience may change the acoustics of the hall significantly, and that a cloakroom may be optional in a warm climate, but critical in a cold one. It also helps designers decompose problems into subproblems that are subject to relatively independent constraints and that can therefore be addressed separately [95]. For instance, the problems of designing the layouts of the

---

[ix] Continental seating places aisles at the sides of an auditorium. Rows are consequently longer and more space between them is required. American seating uses a central aisle, bisecting rows and necessitating less space between them.

backstage area and the “front of the house”[x], while superficially similar, are actually subject to quite different and independent considerations and can be treated separately.

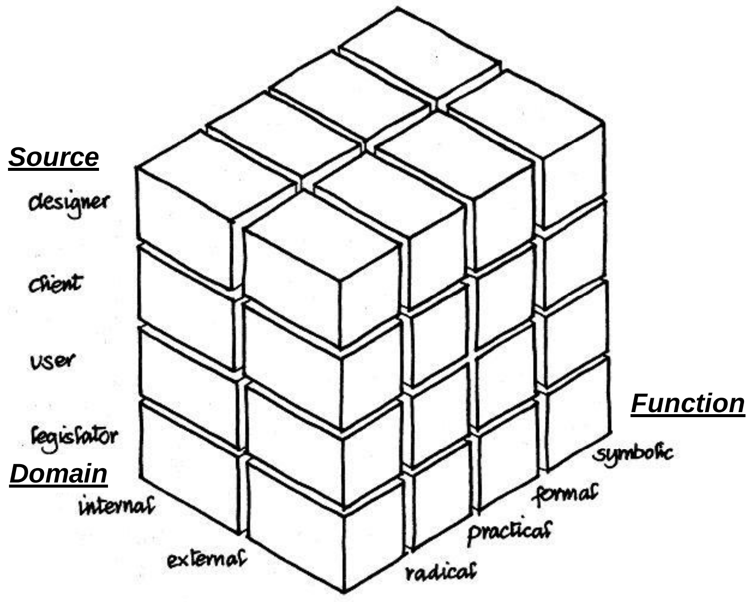
In the design generation phase, knowledge of commonly used solutions, of key elements and of relationships among key elements embodies knowledge of factors that affect typical or significant constraints along with ways of satisfying them. Such knowledge appears to help designers recognize information that is irrelevant to a problem solution [128], apply known solutions or portions thereof [128], and identify critical design elements and suggest ways of manipulating them [128, 227, 248]. For instance, although most architects are familiar with the so-called “7-11 rule” of staircase design (cf. *Design Constraints*, p. 6), an experienced symphony hall designer might recognize that backstage staircases must accommodate female musicians wearing long dresses and carrying valuable musical instruments, and might adjust steps accordingly.

Classifying Constraints

The concept of design constraints is often discussed without a deeper consideration of what it actually represents. However, the concept covers a vast array of influences on design, not all of which are controlled by the designer and not all of which may be articulated explicitly without knowledge of a specific design problem. It is therefore beneficial to develop a deeper understanding of different types of design constraints. This will help to identify types of constraints that can be articulated explicitly and types that provide particularly powerful design knowledge. The classification discussed here is that of Lawson [161] who provides a systematic taxonomy. Reitman [227] describes a set of possible attributes of constraints that are suggestive of classification, but which do not form a systematic system.

---

[x] The portion of a performance hall through which the audience enters, typically containing lobby, ticket office, cloakroom, etc.



This dissertation focuses on invariant constraints in the category of radical, external, user constraints.

Figure 6 Lawson's model of constraints in design problems[xi].

Lawson's Classification of Design Constraints

Lawson [161] has developed a taxonomy of design constraints, drawing on extensive study of design and designers, predominantly in architectural design. He defines three orthogonal dimensions (Figure 6): source, domain and function. These dimensions allow the classification of individual constraints with respect to a specific design situation.

Sources of Constraints

Lawson's first dimension is the *source* of a constraint. The source of a constraint describes who controls the conditions that require the constraint to be satisfied. For example, building codes might require all bedrooms in private residences to have at least one means of outside access, and the person who is to live there might require the master

---

[xi] [161] Reprinted from *How Designers Think*, 3rd ed., Bryan Lawson, p. 107, Copyright (1997), with permission from Elsevier Science.

bedroom to have an eastern exposure. Lawson identifies four sources of constraints (in order of increasing flexibility in whether the imposed constraints must be satisfied): legislator, user, client and designer.

The *legislator* may control laws that dictate specific criteria a design must meet, e.g., building codes that dictate standards of fire safety for private residences or prevent use of asbestos in their construction. At this time, few legislative constraints are imposed on user interface designs, although all must comply with applicable general legislation concerning issues such as truth in advertising, protection of privacy, and pornography.

The *user* of a design is the individual or organization that will actually be using the design to meet their needs. Users impose constraints by virtue of their needs and desires. For example, users' needs dictate that a house to have entrances and exits (usually doors or doorways), while their desires might dictate that doors be of wood. Users are considered the preeminent source of constraints in user interface design and so-called "user-centered design" [199] is the dominant philosophy of human-computer interaction at this time.

The *client* of a design is the individual or organization who has commissioned the design. In the case of user interface design, this is typically a commercial organization by which the designer is employed. Clients may dictate standards to which the design should conform, such as a style defined by other designs, or they may impose other criteria, such as "a radically new look." Most client constraints in user interface designs stem from marketing considerations, e.g., "must conform to interaction conventions of previous releases" or "can't have round buttons," although some organizations have published standards for the design of graphical user interfaces, e.g., the US Department of Defense [113] and IBM Corporation [112].

Finally, *designers* may themselves impose constraints on designs. These generally arise from the designer's design sensibilities and perceptions of what constitutes "good" design. Constraints from this source often reflect codified schools of thought or styles of design [227, 247], wherein convention and tradition define systems of associated constraints. The field of user interface design has not yet evolved such design schools. However, designers occasionally transfer constraints, unconsciously, based on conventions of design from one computational platform to design for another. For example, a designer accustomed to adhering to the constraints imposed by Macintosh™ conventions might place a confirmation (“OK” or “Save”) button in the lower right-hand corner of a dialog box, thus violating the Windows® convention of placing the “Cancel” button in this position.

Domains of Constraints

Lawson’s second dimension for classifying constraints is the *domain* of influence of a constraint. The domain of a constraint is defined according to the relationship between the factors that satisfy the constraint and the problem to be addressed. *Internal* constraints depend entirely on factors “within” the design, i.e., within the designer’s control. They “establish relationships between elements of the object being designed” [161, p. 93]. *External* constraints depend on one or more factors that are “outside” the problem to be addressed and not controllable by the designer. They “relate the designed object to its context” [ibid.].

In the design of a house, for example, the user’s desire to have access to a bathroom from the master bedroom is satisfied through the positioning of the two rooms and connecting doorways—all controlled by the design—and thus imposes an internal constraint. The user’s desire to have morning sun in the bedroom, however, is satisfied through the positioning of the bedroom, its windows and the sun in the morning. The latter—the position of the sun in the morning—is not under the control of the design and the imposed constraint is external.

User interface designers face both internal and external constraints. Published design standards and guidelines often describe internal constraints, for instance, specifying the positions of buttons relative to other buttons and within their containing dialog boxes. Characteristics of humans, such as human cognition, impose extensive external constraints.

Functions of Constraints

Lawson's third and final dimension is the *function* of a constraint. The function of a constraint describes which aspects of the problem solution are affected by the constraint. Lawson identifies four functions of constraints: radical, practical, formal and symbolic.

Radical[xii] constraints "deal with the primary purpose of the object or system being designed" [ibid., p. 103], that is, they affect whether the problem to be addressed is, in fact, addressed. E.g., if there are no entrances to a house, the user cannot make use of the shelter it is intended to provide. Radical constraints are one of the main types of constraints considered in user interface design. In fact, many user-centered design methodologies are aimed at identifying radical constraints, e.g., the numerous methods developed for analyzing user tasks [102].

Practical constraints "deal with the reality of producing, making or building the design; the technological problem" [ibid, p. 104], that is they affect the process of design realization. This includes resource limitations, such as those imposed by budget or time considerations. In user interface design, practical constraints are often imposed by resources of time and money, technical limitations or by the skills and expertise of the engineering organization that is to implement the design.

Formal constraints deal "with the visual organization of the object" [ibid.]. This can, presumably, be generalized to include organization of any type that is imposed for reasons beyond addressing the problem directly, e.g., due to aesthetic considerations. In architecture, such considerations are predominantly visual, but, in user interface design, logical organization often plays a large role. For instance, menus are typically organized by grouping options according to the logical relationships among them. While this is reflected visually (if the menus are presented visually), the fundamental organizing principle is logical. (Note that while the presentation of options may be subject to formal constraints, the selection of options to be presented is subject to radical constraints.)

Finally, *symbolic* constraints deal "with the expressive qualities of design and the use of form and space to achieve specific effects rather than an abstract assembly" [ibid.,

p. 105]. This can be thought of as the philosophical or symbolic “statements” made by the design. For instance, the pointed arch that is a hallmark of Gothic cathedrals “refers us, therefore, to that state of higher awareness in which the mind and the heart find union” [7, p. 41]. User interface designers rarely have the opportunity to make lofty philosophical statements, but seek to convey more mundane messages such as “familiar and friendly” or “new and different.”

Note that radical and practical constraints can be seen as imposing pragmatic limitations on the problem solution, while formal and symbolic constraints impose abstract limitations, e.g., its aesthetics and its emotional effect.

Generality of Constraints

Lawson’s dimensions classify constraints relative to a particular design situation. However, a constraint may also be classified according to how broadly applicable it is. Some constraints apply only to a single situation, while others apply to multiple situations. For instance, the constraints imposed by the structure of a tree on the shape of a tree house are unique to that particular tree and that particular tree house. The constraints imposed by human weight on the construction of a load-bearing platform, however, are the same across all tree houses.

Thus, the a dimension of *generality* is defined here to augment the dimensions offered by Lawson. Generality describes how broadly a constraint applies with respect to a particular class of problems or type of design situation. Unlike Lawson’s dimensions, which are nominal, generality is an ordinal measure. That is, some constraints can be said to be more general than others, without being able to specify how much more. This allows for the definition of three categories. *Inappropriate* constraints apply to none of the problems or situations in a given class of designs. *Variant* constraints apply to some but not all problems in the class. *Invariant* constraints apply to all problems in the class.

For example, the “7-11” rule of staircase design (cf. *Design Constraints*, p. 6) was found to be variant with respect to the class of all staircases, since it may not apply in

---

[xii] Used here in its first meaning of “arising from or going to a root or source” [6].

certain design situations (e.g., in a symphony hall, cf. p. 33). Designers of stage sets, who must often design staircases that fit into small or oddly configured spaces, use an "18 inch" rule. The "18 inch" rule dictates that the sum of the rise and the run of a step must equal 18 inches. It is clearly a more general expression of the anatomical factors underlying the "7-11" rule, and may represent a formulation of the constraint that is invariant with respect to the design of all staircases. Of course, both "7-11" and "18 inch" rules are inappropriate with respect to the design of elevators.

The problem characterization plays a greater role in classifying the generality of a constraint than it does in classification by any of Lawson's dimensions. For example, if the problem is defined as designing an entryway, the laws of natural physics impose constraints whose applicability varies, depending on whether the problem is addressed in a physical or virtual environment[xiii]. However, if the problem is defined as designing an entryway in a physical environment, the constraints imposed by natural physics are invariant.

Since invariant constraints apply to all problems in a class of design problems, it follows that it may be possible to identify them by examination of representative examples of such problems, and that they may be described without requiring knowledge of any specific design situation. They also offer the maximum benefit to designers, as they are applicable to any problems of the given type. They are thus the natural candidates for the present effort to identify design constraints, as well as the group that offers the greatest potential benefit. Human cognition is a major source of invariant constraints in user interface design, and navigational cognition is a major source of constraints in the design of electronic environments.

Key Constraints in User Interface Design

Figure 6 shows Lawson's original model of constraints in design problems. This model, with or without the dimension of generality, can be used for a variety of purposes.

[xiii] Computer-based environments that simulate the physical environment along one or more dimensions, typically at least offering the perception of a 3-dimensional Euclidean space.

Designers might use it to identify and organize constraints in a particular design situation, ensuring that key concerns are identified and addressed early in the design process. Educators might use the model to help design students learn to manage different aspects of design, for instance, creating assignments based on different types of constraints. It can also serve to classify and organize research aimed at supporting design. The last two uses particularly benefit from the incorporation of generality, as both educators and design researchers typically focus on knowledge that can be applied in multiple design situations.

The prominence of user-centered design and its related methodologies, such as task analysis, demonstrate that external, radical, user constraints are a critical category of constraints in the design and development of user interfaces. Because electronic environments are predominantly symbolic, a large proportion of these constraints result from cognition (although those resulting from perception have hitherto received more attention). Most cognitive mechanisms are generalized and employed in a variety of tasks [141], so a large proportion of cognitive constraints can be expected to be invariant across a variety of electronic environments that support different tasks. This dissertation aims at identifying a set of invariant, external, radical, user constraints imposed by navigational cognition on the design of electronic environments in order to support both analytical and generative phases of design.

Other Efforts to Use Design Constraints to Support User Interface Design

A considerable amount of research aimed at supporting user interface design has centered on design constraints, albeit often without a stated intention of doing so. Such research generally addresses constraints in one of four ways. First, a variety of methodologies has been developed that, in effect, help designers to identify and satisfy the constraints that apply to a particular design situation. Second, methodologies have been developed to help designers articulate and preserve constraints that are discovered in one design situation for use in subsequent situations, for instance, during future enhancements or redesigns. Third, a variety of efforts aim, like the present work, at identifying and encapsulating knowledge of specific constraints in order to communicate these to designers. Fourth, a variety of efforts seeks to develop ways of aiding designers in using previously encapsulated constraints.

All four approaches most commonly address radical user constraints, but vary with respect to the domains and generality of constraints addressed. Methodologies for identifying or preserving constraints typically capture both internal and external constraints as well as both variant and invariant constraints. Encapsulated constraints, not surprisingly, are generally invariant, and are either internal, e.g., design standards, or external, e.g., design guidelines. Ways of applying encapsulated constraints typically support invariant internal constraints.

Helping Designers to Identify and Apply Constraints

Methodologies aimed at helping designers to identify constraints primarily support problem analysis. Analytical techniques, such as those developed for analyzing characteristics of users and their tasks (so-called user and task analysis methods) [26, 102, 238], aim at making constraints of specific design situations explicit. Cognitive task analysis, for instance, is a methodology for identifying and describing the goal structures that underlie observed task performance (among other things) [238], that is, to determine the relationships among specific goals and subgoals of a task.

Note that, while this dissertation shares the intent of analyzing characteristics of users and their tasks, the methodologies describe here provide support in gathering and organizing data about behavior, rather than in how to interpret such data. The need of the present effort to understanding navigation as a problem in design is for interpretation (hence the basically synthetic nature of the design knowledge development process). Thus, none of the techniques described are employed overtly, although they may well have had a covert influence.

Narrative techniques allow designers to model key constraints and systems of constraints implicitly. For example, scenario-based design [45] encourages designers to collect and develop detailed narrative descriptions of users' actions and experiences in using the design. The narratives are then used as prototypical cases throughout the design process. The advantage of these approaches is that they capture external and variant constraints (as well as salient non-user constraints), many of which cannot be anticipated without knowledge of the particulars of the design situation. A disadvantage is that designers may spend considerable amounts of time identifying invariant constraints, in effect reinventing the wheel, often repeatedly.

For instance, designers analyzing problems in navigational designs in the physical world often “discover” that a critical problem is that overview maps positioned in the environment are misaligned with the environment (e.g., right on the map corresponds to forward in the environment). However, this “north-up” effect is perhaps one of the most robust effects in experimental navigational psychology. In fact, it is so robust that it has been used as the subject for laboratory exercises for students in introductory psychology courses.

Other methodologies aim at helping designers apply constraints identified within a particular design situation. Such methodologies generally support design evaluation, and range from methods for creating formal specifications of constraints against which candidate designs can be evaluated, such as GOMS-based techniques [132], to methods for engaging expert knowledge during design evaluation, such as techniques for conducting usability inspections [196]. Creating formal specifications presumes that key constraints can be formalized sufficiently to be expressed in a testable specification. This presumption severely curtails the scalability of such techniques [196], so and they do not work well in complex, highly interactive designs that are subject to a multitude of conflicting constraints. Engaging expert knowledge depends on having experts with prior knowledge of the key constraints, either acquired through direct experience or from training based on articulated sets of constraints.

Helping Designers to Preserve Constraints

Methodologies that help designers preserve constraints they have uncovered in a particular design situation usually record the constraints along with either the logic surrounding them or with proven ways of satisfying them. Techniques, such as design rationale capture [179, 189], that record the logic surrounding the constraints preserve the design problems encountered and addressed. They allow problems to be reevaluated and constraints satisfied differently under future circumstances. Techniques that encapsulate partial design solutions, including methods for describing and applying design patterns

[159], allow a designer to employ knowledge of a constraint without needing to understand the actual constraint or to determine how to satisfy it.

Both types of methodologies are invaluable in providing designers with knowledge of constraints that may be applicable to subsequent designs. However, constraints are selected for preservation in a somewhat ad hoc fashion. This allows variant constraints to be captured, preserved and, later, applied on a par with invariant constraints. Since variant constraints may or may not apply to subsequent design situations, their inclusion potentially misdirects attention, hindering rather than helping design innovation. For instance, designers of mechanical type fonts took many years to develop sans-serif fonts, finally recognizing that serifs[xiv] were preserved from brush strokes in hand-written documents, and were not necessary in mechanical printing.

Encapsulating Constraints

Design constraints specific to particular domains have been identified and encapsulated in a variety of ways, typically as design standards or guidelines. These allow constraints to be communicated directly to designers, but provide no support in helping designers satisfy them. Most guidelines and standards are derived from actual design experience [112, 113, 133, 180, 269, 275], so, like constraints captured through design rationale, may be ad hoc. This derivation potentially confounds variant and invariant constraints, increasing the difficulty of their application and the likelihood of misapplication.

A few efforts have sought to derive guidelines or principles for design systematically from psychological evidence [41, 42, 262, 275]. Vinson [275] derives a set of guidelines for the design of virtual environments from descriptions of the elements people have been shown to use in mental representations of physical environments [172]. These guidelines describe manipulations of certain design elements, but do not describe the effect of these manipulations on cognition.

[xiv] "A fine line finishing off the main strokes of a letter, as at the top and bottom of M." [6].

In contrast, the well-known work of Card and Moran [41], and Card, Moran and Newell [42] describes cognitive effects, but does not link them to specific design elements, except in the course of illustration. This work sought to expose the constraints imposed on interaction design by the cognitive mechanisms underlying behavior. This resulted in the *Model Human Processor* (MHP) [42], a description of human information-processing in terms of the subsystems engaged (perceptual, motor and cognitive) and a set of principles of their operation. The model includes estimates—derived from empirical evidence—of the time required for basic operations within each subsystem. For instance, motor system movement, such as arm-finger-hand or head-eye, "consists of a series of discrete micromovements, each requiring about τ_M = 70 [30 ~ 100] msec" [42, p. 34]. The MHP is a performance model of human cognitive behavior, intended to "help us to understand, predict, and even to calculate human performance relevant to human-computer interaction" [42, p. 44]. In use, the model is coupled with a detailed analysis of the cognitive behaviors induced by a particular design, in order to evaluate the performance cost of the design and allow comparisons of design alternatives.

The work of Vinson and of Card, Moran and Newell represent opposite cases of encapsulated constraints. Vinson encapsulates the design elements to be manipulated, but does not provide a means of linking manipulations to performance. Card, Moran and Newell encapsulate performance, but do not provide a means of linking it to actual design elements. Thus, the designer is informed of only one facet of the constraints and is left without the means of generating alternate ways of satisfying them.

Applying Encapsulated Constraints

Previously identified constraints have been encapsulated for use by designers by embedding them—explicitly or implicitly—in design and development tools. Embedding allows constraints to be communicated to designers indirectly, i.e., without the designer necessarily recognizing the constraint, and provides a means of enforcing satisfaction of critical constraints. Fischer [76, 77] embedded design constraints from a limited domain (kitchen layout design) into design tools, known as "design critics," aimed at supporting problem analysis and design generation. Design critics maintain a database of explicitly formulated design constraints and analyze designs continuously as they are being developed. The system notifies the designer of constraint violations as they are identified.

Application frameworks are perhaps the most common means of embedding constraints for the design of electronic environments. The most well-known of these are those that support the development of graphical user interfaces, such as Microsoft Foundation Classes™ (MFC). These embed a set of constraints that were derived from knowledge of human perception during the design of the Star interface [134, 254], and widely distributed with the Macintosh Toolbox™ [5].

The primary difficulty with encapsulating constraints lies in identifying and articulating the constraints to be encapsulated. Often, constraints are identified through lengthy iterative design cycles, possibly lasting years, while the author of the design principles or guidelines gains experience, or the design or development tool is refined through use and revision. In other cases, constraints are derived systematically from an existing body of knowledge. This latter, however, requires a thorough analysis of the given knowledge.

Relationship to Present Work

The goal of the present work is to derive a set of constraints systematically. The constraints identified are initially expressed as a set of principles that link specific design elements and their properties to cognitive task performance. It is similar to the work by Card, Moran and Newell, but seeks to overcome the limitations of that work by using cognitive tasks rather than cognitive mechanisms as the unit of analysis. This allows links between cognition and specific design elements to be identified and described more readily. The work complements other efforts to support design with constraints. It reduces the number of constraints that designers must identify and preserve, allowing methodologies aimed at identifying and preserving constraints to be targeted at lesser known or variant constraints. It provides a known set of constraints that may be in tools aimed at helping designers apply constraints, potentially enhancing the use of the given set of constraints as well as use of the tool.

Behavior, Cognition and Design Constraints

The goal of the present work is to articulate a set of design constraints that cognition imposes on design. The first step toward this goal must necessarily be to describe the cognitive activities in which the user of the design must engage. As the goal is to identify constraints from actual rather than ideal behavior, this description must reflect actual rather than ideal cognition. However, cognitive activity is not directly observable, and the present work, like much work in cognitive science, rests on the assumption that cognitive activity can be inferred from observable manifestations, such as behavior, eye movement or bioelectrical activity [4, 184].

Levels of Description of Cognitive Activity

The present work, as intimated earlier, distinguishes between cognitive "task," cognitive "behavior" and cognitive "mechanism." *Cognitive task* is used here to refer to a set of mental functions to be performed, described in terms of the goals to be achieved by performing those functions. For example, a cognitive task might be to calculate the product of the numbers 3 and 2. *Cognitive behavior* is used to refer to a pattern of mental actions that changes mental state or initiates physical action. For example, the goal of multiplying 3 by 2 can be achieved by remembering the result from previous experience, by visualizing three units lined up twice and mentally counting the result, or by remembering that the product of any number with 2 is equal to the number added to itself. *Cognitive mechanism* refers to the mental and physiological structures and processes by which cognitive behaviors are effected. For example, all three behaviors described rely, to some extent, on physiological memory, while only the second also relies on mental visualization.

Cognitive task, behavior and mechanism constitute three different levels of describing cognitive activity[xv]. While each may be considered independently, they may

---

[xv] Anderson [3] presents a detailed discussion of levels of cognitive theory and a comparison of different decompositions of description. The three levels considered here

also be considered in terms of each other. Tasks may be described in terms of the behaviors invoked to accomplish the goals (e.g., retrieve the rule that that the product of any number with 2 is equal to the number added to itself from memory, retrieve the sum of 3 and 3 from memory). Behaviors may be described in terms of the goals they achieve (e.g., convert 3 * 2 to 3 + 3, calculate 3 + 3) or the mechanisms that are engaged (e.g., retrieve result directly from memory or visualize operation). Mechanisms may be described in terms of the behaviors they support (e.g., retrieve information).

The goal of design is to support the achievement of goals, that is, to support tasks. This may entail supporting certain behaviors or it may require fostering and supporting new behaviors. Thus, from a design perspective, the aim is to describe the cognitive tasks that underlie observed behavior. Note that this differs from most efforts in psychology or cognitive science, whose aim is to describe cognitive structures and processes that can account for observed behavior [3, 184]. Because the goal of the present work is to support the design of novel environments, it is important to dissociate tasks induced by a particular environment from those that result from fundamental cognition. This minimizes the risk of archaistic design—design that unnecessarily retains properties of preceding designs—a recognized risk of techniques such as Cognitive Task Analysis that rely on analysis of existing practices and behaviors [4].

Like much work in both cognitive science [184] and human-computer interaction [4, 132], the present work assumes that tasks can be decomposed into subtasks. This rests on the assumption that goals can be decomposed hierarchically into a structure of subgoals. Identifying subgoal structure from observed behavior rests on the assumption that human behavior is fundamentally goal-oriented, that goals can be inferred from observed behavior, and that subgoals are reflected in a "hierarchical organization of behavior" [184, p. 15]. Once the subtasks have been described, it is possible to examine how each is affected by properties of the external environment. These relationships can again be inferred from observed behavior. Such inferences describe the relationship

---

are consistent with other decompositions, although some offer a further distinction between mental and physiological mechanism. The terminology used here is in keeping between achievement of goals—task performance—and environmental features, in other words, the design constraints sought by the present work. The two steps of inferencing are reflected in the design knowledge development process for understanding navigation as a problem in design (Figure 2).

Cognitive vs. External Task

The focus here is on cognitive tasks and behaviors, that is, on the mental behaviors of a human. These are assumed, in general[xvi], to serve *external tasks*—tasks whose goals include effecting change outside the mind, including, potentially, changes in the minds of others. Because cognitive tasks serve external tasks, it can be assumed that there is some correspondence between the two. However, the two are not identical. A cognitive task may be engaged in a variety of external tasks, and an external task may be accomplished in different ways that engage different cognitive tasks. For example, the external task of buying shelving might engage the cognitive task of multiplying 3 by 2 or it might engage the entirely different set of tasks entailed in using a slide rule to do so. The same two cognitive tasks, conversely, may be engaged when buying shelving or when deciding to go tide-pooling.

It is thus necessary for a designer to understand the relationship between the external task the design is to support and the cognitive task that must or might be engaged in order to accomplish it. This characterizing external tasks according to the cognitive tasks upon which they depend as well as describing what characteristics of external tasks determine which cognitive tasks might be invoked. Such relationships will be discussed to a limited extent for certain subtasks of navigation (*External Tasks and Cognitive Tasks*, p. 62). An attempt to characterize the relationships between external tasks and all

---

with common uses in human-computer interaction and differs from those used in cognitive science (as described by Anderson).

[xvi] Some few cognitive tasks, e.g., the interpretation of dreams, do not necessarily serve external goals.

navigational subtasks is beyond the scope of the present work and is deferred to future work.

Navigation: A Cognitive Task

In order to understand the constraints a cognitive task imposes on design, it is necessary to understand the cognitive task itself. The cognition of navigation has been studied extensively by a variety of disciplines for a variety of purposes. This has resulted in a plethora of conceptions of “navigation,” an array of conflicting terminologies, and almost religious convictions concerning the roles and relative significances of various cognitive subtasks. The purpose of this section is to develop a conceptual model of navigation as a fundamental cognitive task, that is, to lay out the cognitive behaviors and processes that are inherent to navigational cognition. To ensure that the model reflects actual rather than ideal behavior, the model based on analysis of empirical evidence of cognitive behavior, rather than philosophical reflection on the external goals and problems of navigating.

Two large bodies of literature on navigation are omitted from the analysis, as they embody preconceived models of the navigational task. The first describes specific techniques or technologies for navigating in the physical world including different types of navigational systems, e.g., technology-based (global positioning, radar, sonar, etc.), knowledge-based (sun tracking, star maps, topographic maps, etc.), and perception based (audial, visual, gradient perception, etc.). The literature also details different strategies for employing these systems, e.g., dead reckoning (using movement to infer position), pilotage (using external signals such as landmarks), and beacon following (moving directly toward a given object or environmental feature).

Most of these technologies and strategies represent particular ways of solving physical navigational problems that assume properties of the physical environment. For instance, the need to “know” one’s current location in order to move to another position is often assumed to be a fundamental problem in navigation [69, 195], but is, in fact, not necessary in environments, such as many electronic systems, where one need only be able to name one’s destination in order to get to it. Fundamental cognitive behaviors are thus conflated with behaviors induced by the physical environment. Dissociating the two would not only entail analysis of observed behavior, but also require developing theories about the conditions that induce such behaviors.

The second body of literature is from the fields of cognitive science and robotics. It aims at developing computer models that simulate navigational cognition or navigational behavior. This literature provides insights into cognitive mechanisms, behaviors and tasks that could account for observed behavior as well as revealing the cognitive problems that specific navigational strategies engender. However, it does not provide any evidence for whether human cognition relies on any of these. Thus, while it may be illuminate the problems of navigation, it cannot be relied upon to provide evidence for what humans need to be able to navigate.

These omissions notwithstanding, a large body of evidence remains that details observations of navigational behavior under both controlled and field conditions, and which seeks to expose the underlying cognitive tasks and behaviors. It is examined in three phases. First, five cognitive behaviors that are commonly assumed to be associated with navigational cognition are identified, along with relationships among them. These behaviors and their interrelationships are then related to four cognitive tasks that are commonly considered subtasks of navigation, to form a model of navigation as a cognitive task. Finally, possible relationships between the cognitive task of navigation and several external tasks that are commonly viewed as navigational are considered.

By and large, the analysis reveals considerable conceptual agreement obscured by widely varying and, often, contradicting terminological uses. The primary difficulty thus lies in introducing a unified vocabulary. A second difficulty is to reconcile a small but significant difference between the design-oriented model of navigation developed here and the psychology-oriented model that is commonly assumed. The analysis conducted here suggests that this difference is represents differences between a design model and a psychological model rather than a fundamental inaccuracy in either.

Cognitive Behaviors

Most, if not all, literature reporting on navigational and spatial cognition exposes a variety of cognitive behaviors that are considered part of or essential to navigation. For example, Passini [211, 213], drawing on extensive observations of navigational behavior in the physical world, describes four behaviors: "I propose that spatial orientation or the semantically more appropriate term of wayfinding be defined as cognitive processes comprising three distinct abilities: a *cognitive mapping* or *information-generating* ability that allows us to understand the world around us; a *decision-making* ability that allows us to plan actions and to structure them into an overall plan; and a *decision-executing* ability that transforms decisions into behavioral actions" (italics added) [213, p. 46].

Downs and Stea [64], surveying and synthesizing research on cognitive mapping, suggest that this process can be decomposed into several behaviors: "Cognitive mapping is a process composed of a series of psychological transformations by which an individual *acquires, codes, stores, recalls, and decodes information* about the relative locations and attributes of phenomena in his everyday spatial environment" (italics added) [64, p. 9]. McDonald and Pellegrino [182], similarly reviewing research on cognitive maps and spatial cognition, highlight behaviors that make use of such knowledge: "These representations, commonly known as cognitive maps, are used in *planning* and *directing movement* through the environment" (italics added) [182, p. 47]. Finally, Chown et al. [51], also discussing how spatial knowledge is used during navigation, state, "Human wayfinding can be broken down into four component problems: *landmark identification, path selection, direction selection,* and *creating abstract environmental overviews*. *Solutions to* the first three of *these problems* are essential to human wayfinding" (italics added) [51, p. 2].

These examples provide a representative laundry list of the types of behaviors that are examined and considered part of or essential to navigation:

- *cognitive mapping or information-generating*
- *decision-making*
- *decision-executing*
- *acquiring information*
- *coding, storing, recalling, and decoding information*

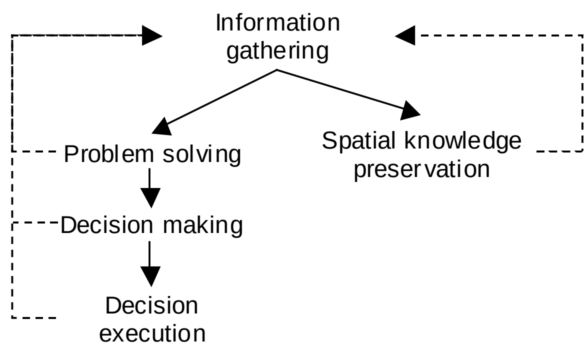
- *planning movement*
- *directing movement*
- *identifying landmarks*
- *selecting paths*
- *selecting directions*
- *creating abstract environmental overviews*
- *problem-solving*

Categorizing the specific behaviors reported in the literature suggests that they represent five general behaviors:

- *acquiring information (identifying landmarks)*
- *coding, storing, recalling, and decoding information (cognitive mapping; creating abstract environmental overviews)*
- *problem-solving (information-generating; identifying landmarks)*
- *decision-making (planning movement; selecting paths, selecting directions)*
- *decision-executing (directing movement)*

These categories are confirmed by the assumptions—stated explicitly in many cases—made in the literature. One common viewpoint considers four of these behaviors essential to navigation: acquiring information about the environment, reasoning about spatial relationships, making decisions about movement, and directing movement between locations [31, 48, 51, 64, 90, 137, 182, 201, 211, 245]. A distinct, but overlapping, viewpoint adds the preservation of spatial knowledge to this set [48, 51, 88, 97, 140, 172, 201, 213, 245, 256, 281]. Five behaviors thus seem to be relevant to navigation: information-gathering, problem-solving, decision-making, decision-execution and spatial knowledge preservation.

(Navigational) *information-gathering* is the process of collecting information about the environment, such as where places and things are and how they are related spatially [31, 48, 51, 64, 90, 141, 211, 256]. (Navigational) *problem-solving* and *decision-making* are the processes of using the available information to develop plans—sequences of movement—for getting to different locations and choosing among them [31, 48, 51, 81, 87, 174, 182, 201, 212, 210]. (Navigational) *decision-execution* is the process of carrying out the chosen action plan [31, 48, 87, 174, 212]. This includes controlling movement and verifying that the results of actions are as expected. *Spatial knowledge preservation* is the process of preserving spatial knowledge about an



Solid arrows show dependencies of behaviors while dotted arrows show information feedback.

Figure 7 Relationships among navigational behaviors; derived by analysis of existing psychological evidence.

environment [48, 88, 97, 140, 172, 201, 213, 256, 281]. This includes preparing knowledge for preservation, assimilating it with prior knowledge, and actually preserving it [64, 107, 182].

Note that the general term "spatial knowledge preservation" is used here to suggest that knowledge may be preserved by other means than mentally. However, it is intended to include mental spatial knowledge preservation—*cognitive mapping*. As the above quotations intimate, cognitive mapping has been studied extensively and is considered a central element of spatial cognition [51, 64, 87, 107, 119, 182, 226, 245, 270]. The structure and both ontogenetic and individual development of *cognitive maps*—mental representations of spatial information that includes topographic knowledge—have been of particular interest to psychologists [64, 97, 107, 245, 270]. The attention to cognitive mapping in psychology has resulted in corresponding attention in design work [18, 50, 69, 103, 121, 127, 166, 192, 254, 257, 275]. Due to its prominence in spatial cognition, cognitive mapping has often been assumed to play a similar critical role in navigational cognition. A question posed by the present work, however, is whether the importance of cognitive maps is inherent to navigational cognition or induced by properties of the physical environment.

Relationships among Cognitive Behaviors

Although few efforts have focused specifically on the relationships between these five cognitive behaviors, such relationships emerge from empirical studies aimed at understanding them individually. This evidence reveals both parallelisms and sequential dependencies among the five behaviors (Figure 7).

Information-gathering is necessary to both problem-solving [31, 48, 81, 87, 213] and spatial knowledge preservation [51, 64, 172, 201]. For instance, Passini, in characterizing the problem-solving component of navigation, assumes the prior availability of spatial information: "An identified wayfinding problem involves both a task and spatial information. We can say that the wayfinding task is interpretation of the task *in the light of the spatial information*" (italics added) [211, p. 24]. Downs and Stea describe cognitive mapping precisely as the processing of available information: “The individual receives information from a complex, uncertain, changing, and unpredictable source via a series of imperfect sensory modalities operating over varying time spans and intervals between time spans. From such diversity the individual must *aggregate information* to form a comprehensive representation of the environment” (italics added) [64, p. 10].

While this might presuppose two distinct types of information-gathering or, at least, two concurrent processes of the same type, overwhelming evidence suggests that a single information-gathering process serves both purposes [44, 67, 84, 140, 169, 201, 213, 226, 245, 267]. Passini [213] identifies three sources of environmental information: direct perception, preserved spatial knowledge, or inferences based on information from either or both of these sources. This is supported by the findings of Burns [31] and Lynch [172], and clearly illustrates that spatial knowledge preservation, while not necessary to information-gathering, may nonetheless precede it. Note that, while spatial knowledge preservation is the processing and integration of available information [51, 64, 172, 201], problem-solving often requires compensating for missing information [51, 64, 81, 201, 213].

Problem-solving precedes decision-making (as these terms are used here[xvii]) and decision-making precedes decision-execution [31, 48, 57, 67, 210]. This is described clearly by Burns, discussing the process of navigating while driving: “The environmental information is used to assess the situation. In this assessment, drivers consider their progress, orientation and path options. [I.e., solve the problems necessary to ascertaining their present status.] Once they have assessed the environmental information, they then attempt to select the most appropriate path and direction in order to travel to their intended destination. After the decision is made drivers must execute it” [31, p. 210].

Gärling, Böök and Lindberg, in studying the relationships between behavior and the knowledge represented in cognitive maps, [87] describe navigational problem-solving and decision-making as the formation of “travel plans”—specifications of how to get from one place to another. They argue[xviii] that “the formation of travel plans leads to inferences that are stored in the cognitive map and that, in a sense, constitute new knowledge about the environment” [87, p.25], i.e., that problem-solving may yield new information. They also assert that the travel plans themselves—the products of decision-making—are information, and are preserved in cognitive maps. Travel plans correspond to the general concept of *route knowledge*—knowledge of “habitual lines of movement and familiar lines of travel” [245, p. 24] which has generally been found to be a key form of preserved spatial knowledge [51, 84, 98, 107, 118, 155, 182, 226, 245, 258, 260].

Gärling, Böök and Lindberg point out that decision-execution also yields information: “The main point is that the specification and revision of travel plans during their execution leads to the acquisition of new information about the environment by direct observation” [87, p. 23]. This view is endorsed by Siegel and White: “Actual

---

[xvii] Problem-solving and decision-making are interrelated and, often, one is considered to be subsumed by the other. In some views, problem-solving is the process necessary to generating a set of options, but is not complete until an option has been selected. [193]. In other views, decision-making is the process of selecting from a set of options, and may determining what options are available [146]. The two processes are, typically, portrayed as iteratively alternating [146, 193, 235].

[xviii] Their subsequent work validates this assumption.

locomotion in space appears to be almost an essential condition for the construction of spatial representations” [245, p. 26]. Thus, problem-solving, decision-making and decision-execution may all precede information-gathering.

The spatial information generated by problem-solving, decision-making, and decision-execution is frequently collected and preserved as spatial knowledge (as suggested by Siegel and White, above). Indeed, such knowledge preservation may be automatic and subconscious [44, 84, 98, 109, 267]. However, there is considerable evidence to show spatial knowledge may be preserved without engaging in these behaviors [68, 73, 97, 120, 230, 267]. For example, Thorndyke and Hayes-Roth [267], in a classic study, showed that spatial knowledge preservation can be induced by study of maps of a physical environment as well as by direct experience, although they showed qualitative differences in the knowledge preserved. This study was replicated by Ruddle, Payne and Jones [230] in a virtual environment, with similar results.

Other evidence shows that complex spatial knowledge may not result from spatial experience. E.g., Moeser [187] showed that many long-time nursing staff at a particularly complex hospital had not developed cognitive maps of the building, although they had developed functional route knowledge. Rand [226] demonstrated a similar lack of integrated cognitive maps among taxi drivers in the city of Worcester. Conversely, spatial knowledge preservation may not precede problem-solving, decision-making and decision-execution. Best [25], Dada and Wirasinghe [57], and Løvås [174], for instance, all studied people’s ability to navigate environments of which they have no prior knowledge, and found that success rates were much higher than random chance would allow. Furnas [80, 81], drawing on human information-processing theory, developed a theory of the environmental information that would allow such behavior.

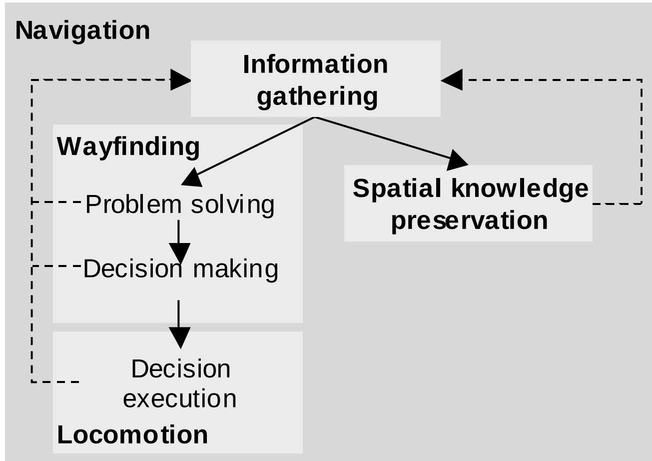
In short, the evidence indicates that spatial knowledge preservation and problem-solving/decision-making/decision-execution are independent although concomitant behaviors. That is, while spatial knowledge preservation may result from problem-solving, decision-making and decision-execution, it is not a precondition for these behaviors, and they, similarly, are not prerequisite to spatial knowledge preservation. This yields the relationships among the five behaviors shown in Figure 7.

Cognitive Tasks

The behaviors just described—gathering information, storing information, solving spatial problems, making decisions and executing decisions—may be engaged for a variety of purposes. In the context of navigation, however, they all serve one or both of two goals: “to facilitate movement and travel” [87, p. 3] or “to form a comprehensive representation of the environment” [64, p. 10]. Navigation is commonly described as comprising three distinct cognitive tasks [48, 97, 201, 211]: directing movement, determining what movement is necessary or desirable, and processing and recording information and knowledge for future use.

The most basic of these subtasks is *locomotion*— the task of directing purposeful movement. As intimated by Siegel and White (cited above), locomotion is an essential and defining subtask of navigation: “Actual locomotion in space appears to be almost an essential condition …” [245, p. 26]. Locomotion invokes decision-execution behavior [31, 48, 87, 174, 211]. *Wayfinding*—the task of determining what movement is necessary or desirable in order to accomplish a task—is also an essential and defining subtask: "Wayfinding, quite on the contrary, is a dynamic affair; it points to the cognitive processes involved in reaching destination [sic.]” [211, p. 22]. Wayfinding invokes problem-solving and decision-making behavior [31, 48, 98, 97, 174, 201, 211, 277]. *Spatial knowledge preservation*—the task of processing and recording information and knowledge for future use—is an important and commonly invoked subtask: “Although cognitive maps are useful for a wide variety of reasons, their fundamental purpose is wayfinding” [51, p. 1]. Spatial knowledge preservation, not surprisingly, invokes spatial knowledge preservation behavior [51, 64, 172, 87, 97, 107, 140, 182, 213, 245, 256].

Information-gathering is not conventionally characterized as a separate task. Studies focused on spatial knowledge preservation typically consider information-gathering a subtask of spatial knowledge preservation [51, 87, 140, 182, 245, 256], while studies focused on wayfinding consider it a subtask of wayfinding [31, 48, 98, 97, 174, 201, 211]. However, the evidence suggests, as described above (*Relationships among Cognitive Behaviors*, p. 53), that a single information-gathering behavior serves both problem-solving and spatial knowledge preservation needs. It is thus here considered a



Solid arrows show dependencies of behaviors while dotted arrows show information feedback.

Figure 8 Design-oriented model of navigation showing fundamental relationships between navigational behaviors and tasks.

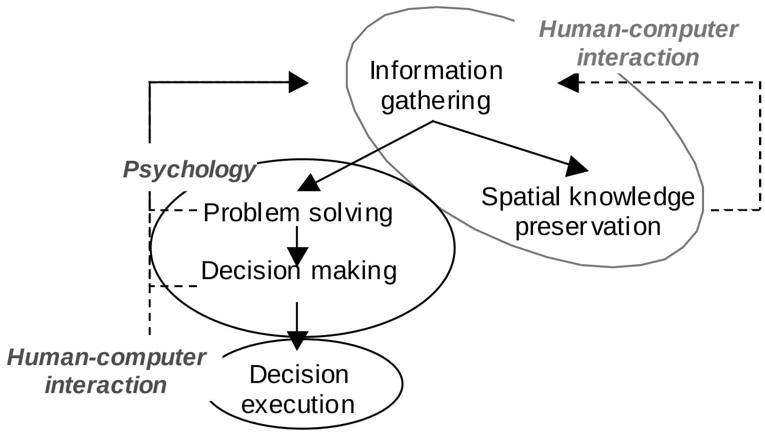
separate task, namely, *information-gathering*—the task of collecting information about the environment. Separation of information-gathering from other navigational tasks is supported by Hutchins' study of team navigation [124]. He describes different navigational roles that are assigned to different individuals aboard a navy ship. As described, most of these roles perform a single navigational task: The Navigator (wayfinding), The Assistant to the Navigator (wayfinding), Navigation Plotter (spatial knowledge preservation), Navigation Bearing Recorder/Timer (spatial knowledge preservation), Starboard Pelorus Operator (information-gathering), Port Pelorus Operator (information-gathering), Restricted Maneuvering Helmsman (locomotion), Quartermaster of the Watch (spatial knowledge preservation), Restricted Maneuvering Helmsman in After Steering (locomotion), and Fathometer Operator (information-gathering, spatial knowledge preservation).

A Design-Oriented Model of Navigation as a Cognitive Task

The relationships between the cognitive behaviors of navigation, and between cognitive behaviors and tasks result in the design-oriented model of navigation as a cognitive task shown in Figure 8. This model comprises four tasks, adding information-gathering to the three tasks commonly detailed [48, 97, 137, 201, 211]. The task of information-gathering comprises all behaviors associated with gathering information about the spatial attributes of the environment, regardless of the source of the information. This information is then employed by either wayfinding or spatial knowledge preservation, or both. Wayfinding comprises the spatial problem-solving and decision-making entailed in figuring out where to go and how to get there. Spatial knowledge preservation comprises all behaviors associated with preserving spatial information for future use, including transforming and integrating it with existing knowledge. Locomotion is the execution of wayfinding decisions, which comprises all behaviors associated with actually getting there.

A key implication of this model is that all four tasks may be performed simultaneously, that is, information may be gathered while problems are being solved and decisions made. At the same time, information may be preserved for future use. Moreover, this may all take place while moving. However, information-gathering and either of wayfinding or spatial knowledge preservation are sequential with respect to a particular piece of information, and wayfinding and locomotion are sequential with respect to a particular decision.

This description makes the slightly misleading implication that wayfinding is entirely independent of preserved spatial knowledge. “Spatial knowledge” is commonly used to denote knowledge of a particular environment and comprises three forms of knowledge: *landmark* (knowledge of salient spatial reference points), *route* (procedural knowledge of how to get from one point to another) and *survey* knowledge (topological knowledge) [172, 182, 245]. It does not include knowledge of *spatial schemata* [217, 288]—knowledge of prototypical environmental patterns [62, 101, 181, 288]. Spatial schemata might include knowledge of typical spatial relationships in certain types of buildings, e.g., “most city-dwellers know that in a large traditional department store the coffee shop is typically located on the top floor. Escalators are typically located in the center of the building, while elevators will be located on one wall” [288, p. 89]. Spatial schemata are acquired over repeated exposure to different environments that exhibit similar properties but do not represent any one particular environment.



Dotted grey lines indicate isolated occurrences.

Figure 9 Different uses of "navigation."

Without either spatial knowledge, as traditionally defined, a spatial schemata believed to be relevant to a given environment, or some schema for recognizing and interpreting environmental information (e.g., the knowledge needed to recognize and interpret "arrow" signage), there is no way for directly perceived information to be interpreted in a navigationally meaningful way. "Wayfinding" would be reduced to random guessing. Thus, even though the model does not suppose that spatial knowledge preservation is prerequisite to wayfinding, it does presume that some prior knowledge is available during wayfinding that allows interpretation of and inferencing from directly perceived environmental information.

Navigation by Any Other Name

Terminological differences present a major difficulty in understanding literature related to navigation. "Navigation" and "wayfinding," in particular, have been used in a variety of ways and their intended meanings are not always made clear. Rather than representing fundamental differences, however, these differences seem to reflect disciplinary viewpoints and differing interests in the navigational subtasks.

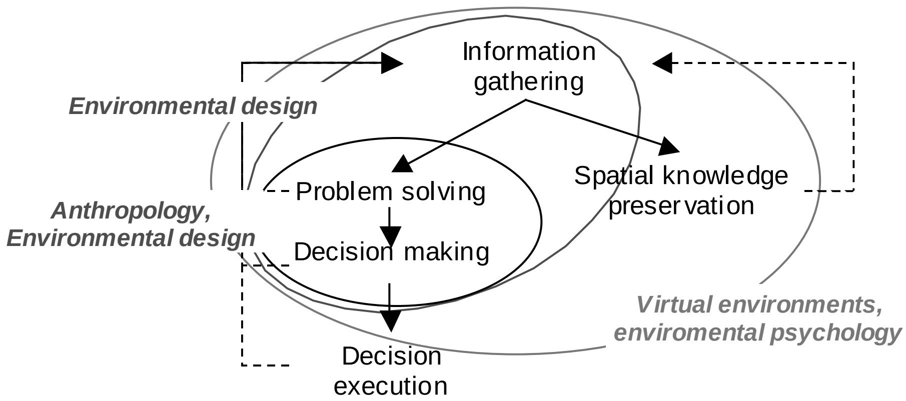
"Navigation," in the human-computer interaction literature, generally refers to what is here called locomotion [18, 37, 48, 85, 104, 139, 255], and, in a few isolated cases, to what is here called spatial knowledge preservation [192, 219, 256]. Psychologists, however, generally use "navigation" to refer to what is here called wayfinding [63, 67, 135, 173, 201, 221, 258, 265, 267, 277, 281, 283]. Figure 9 illustrates these different uses of "navigation."

The present use of "wayfinding" conforms to its use by anthropologists [92, 124] and by disciplines concerned with environmental design, such as architecture, urban planning and geographic information systems [31, 36, 88, 97, 101, 174, 181, 204, 217, 278]. However, it has also been used variously to combine information-gathering, spatial knowledge preservation and wayfinding [48, 97], or information-gathering and wayfinding [213]. In singular cases, "wayfinding" has been used to denote what is here called locomotion [109] and navigation [156]. Figure 10 illustrates these different uses of "wayfinding."

Comparisons to Other Models of Navigation

Barring differences of terminology, the model presented here is consistent with the model of "wayfinding" (navigation)[xix] presented by Burns [31], although he distinguishes between information-gathering by direct perception and information-gathering from memory retrieval, and only considers cognitive maps as a source or means of preserved knowledge. It is also consistent with the model of "wayfinding" (information-gathering, wayfinding and locomotion) laid out by Hutchins [124]. However, it differs from most other models of cognitive behaviors related to navigation in one of two ways. Models that include spatial knowledge preservation typically subsume information-gathering under spatial knowledge preservation [48, 51, 90, 192, 213, 245, 256]. Models that include navigational problem-solving and decision-making typically consider spatial knowledge preservation an essential precursor to problem-solving and decision-making [48, 88, 213, 281]. These differences combine to yield the psychology-oriented model shown in Figure 11.

[xix] In order to disambiguate terminology, yet allow recognition by readers familiar with the cited work, the authors' original term is enclosed in quotation marks followed by its interpretation in the present terms, when necessary.



Dotted grey lines indicate isolated occurrences.

Figure 10 Different uses of “wayfinding.”

The discrepancies between the design-oriented model of navigation and the psychology-oriented model can be explained by differences in their intended purposes. Most other models are intended to account for all observed behaviors. The present model, in contrast, is intended to account only for fundamental behaviors and specifically seeks to discount those that are induced by any particular type of environment. Most models are based on behavior observed in the physical environment where the benefits of preserving spatial knowledge and drawing on preserved knowledge are considerable [67, 140, 152].

External Tasks and Cognitive Tasks

Navigation is undertaken for one of two purposes [137, 225, 281]: "..., we suggest that our data must deliberately reflect the distinction between *the general understanding of layouts* and *the search for particular destinations*" (italics added) [217, p 556]. These purposes reflect a small number of generic external tasks, including tasks known as “searching” and “browsing.” These generic tasks, in turn, are undertaken to meet the needs of specifically defined external tasks, as in “searching for the restroom,” or “just browsing, thanks.” Designers, ultimately, begin with knowledge of the external tasks to be supported. They must use this knowledge to determine what cognitive tasks should be supported, which allows them to determine which design constraints are applicable. Thus, it is helpful, for design purposes, to characterize the external tasks that the cognitive tasks may serve, and to describe the relationships between the two.

Searching, Finding, Target Acquisition

The “destination” that is sought, if the purpose of the navigation is to search for a particular destination, must correspond to some spatial location, at a given point in time. However, its definition may allow or require multiple spatial locations to fit the need, for instance, if the destination is a “scenic drive,” the desired location actually comprises a series of locations, and several such series may be available. It might also be defined relative to stable or changing features of the environment (e.g., “a ford across the river,” “the eye of the hurricane”) or its contents (e.g., “where the tiger is”). “Destination” is used to mean the spatial location(s) that meet the defining criteria at any given point in time, i.e., to cover all these cases.

“The search for particular destinations” may be divided into three separate external tasks depending on the circumstances under which it is undertaken. The navigator may believe that they “know” how to reach the destination, or they may lack prior information or certitude in such knowledge. For example, the player may go to the closet because they “know” that is where the ball is. This is the external task of *finding*—going to a location or object within the environment with confidence in the knowledge of where it is or how to get to it [15]. If the ball turns out not to be in the closet, the player searches for its location without “knowing” where it is. This is the external task of *searching*—seeking a location or object within the environment that meets certain criteria without certitude in prior knowledge of where it is or how to get to it [225].

Note that finding differs from *target acquisition*—guiding oneself or some other object to a location or object that is in the current view (i.e., perceptually available). Catching the ball or running to kick it are examples of target acquisition. Target acquisition is linked closely to the cognitive task of locomotion. It represents execution of decisions regarding which location to reach and how to reach it. While it may entail problem-solving and decision-making, these are concerned with controlling movement rather than with determining where to go and how to get there. Because target acquisition is primarily a locomotive task, it will not be considered further, at present.

Finding and searching, in contrast, are linked more closely to wayfinding. Finding involves a simple type of wayfinding problem-solving and decision-making that includes reconciling environmental information with the expectations established by the prior knowledge and verifying that the expectations are being met. It may also require more complex problem-solving and decision-making regarding locomotional options that present themselves. This must, at least, verify the (original) decision not to take them. That finding involves this latter type of problem-solving and decision-making is supported by evidence that the number of wrong turns made along a known route increases as the number of possible turns along the route increases [25, 174, 204].

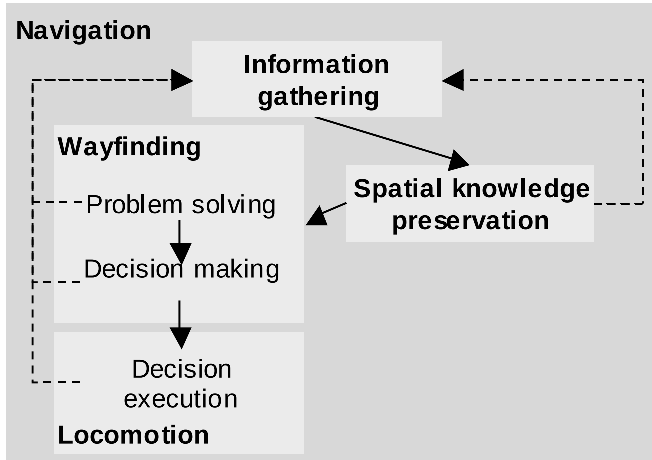
Searching and wayfinding are so closely related as to appear synonymous, and are often confounded in popular use. Wayfinding, however, is a cognitive task associated with navigation, and may be undertaken for tasks other than searching. Searching is an external task that may be accomplished by means other than navigating, e.g., using query-based methods [137], that do not entail wayfinding problem-solving and decision-making.

Browsing

Navigation may also be undertaken in order to gain some understanding of the contents or spatial structure of the environment—"the general understanding of layouts." This corresponds to the external task of *browsing* [225]—seeking to gain knowledge of the contents or structure of the environment. Like searching, browsing may be accomplished by means other than navigation, for instance, by using information visualization tools that display different types of structure and relationships among them [40]. Browsing is closely related to the cognitive task of spatial knowledge preservation.

Searching, Finding and Browsing

Searching, finding and browsing are often conflated and, consequently, often confounded. However, rather than being different aspects of one task, they are generally two tasks interleaved. Searching or finding may be embedded in a browse task, such as when the mapping between destination definition and spatial location is contingent on environmental availability. For instance, finding the ball with which to play, may depend



Solid arrows show dependencies of behaviors while dotted arrows show information feedback.

This model assumes that spatial knowledge preservation *must* precede wayfinding, suggesting that it is not possible to navigate directly from environmental information. This is in contrast to the design-oriented model of navigation (Figure 8), which suggests that spatial knowledge preservation and wayfinding may take place simultaneously.

Figure 11 Psychology-oriented model of navigation as a cognition task common showing commonly assumed relationships among navigational tasks [48, 97, 201].

on which balls are available and how readily available they are (e.g., "I couldn't find the softball, but I found the soccer ball."). In such cases, browsing and searching/finding alternate—browsing the contents of the environment, and then seeking a particular location based on the outcome.

Conversely, a browse task may be embedded in a search or finding task, such as when environmental knowledge gained while seeking an object or location is beneficial in some way, e.g., learning about other sports equipment in the course of finding the ball (e.g., "I didn't know we had a croquet set, let's set that up after lunch."). Browsing and searching/finding also alternate in such cases, but the process is one of seeking a particular location, irrespective of what is encountered along the way, alternating with noticing what is encountered. Browse tasks are often embedded in searching and finding tasks merely by virtue of environmental design. For instance, everyday finding tasks, such as getting to a workplace in the physical world, automatically invokes a browsing task; Who would not like to have the option of stepping out through their front door into their destination, be it workplace, grocery store or playground?

Implications for Design

The close connections between searching/finding and wayfinding, and between browsing and spatial knowledge preservation implies that searching and finding tasks can be facilitated by supporting wayfinding in design, and browsing can be facilitated by supporting spatial knowledge preservation. However, widespread acceptance of the psychology-oriented model of navigation that presumes that spatial knowledge preservation is a precondition for wayfinding (Figure 11) has led to a plethora of efforts seeking to facilitate searching by supporting spatial knowledge preservation [18, 50, 69, 103, 121, 127, 166, 192, 254, 257, 275]—typically by providing complex overview information of the environment or its structure, e.g., through maps. Far fewer efforts seek to facilitate searching by supporting wayfinding [29, 30, 49, 188, 225], e.g., by using predictive techniques to adapt information displays to user needs [29, 49].

The design-oriented model of navigation (Figure 8) suggests that supporting spatial knowledge preservation only facilitates searching indirectly. As preserving spatial knowledge incurs a cognitive cost that increases with the amount of information retained [169], supporting it may actually introduce unnecessary cognitive overhead in searching and finding tasks. This is confirmed by empirical evidence that searching performance—measured in terms of how quickly the location is found—may be improved by reducing opportunities for spatial knowledge preservation [277].

The design-oriented model of navigation similarly suggests that supporting wayfinding only facilitates spatial knowledge preservation indirectly. This, however, is contradicted by empirical evidence that shows that browsing performance—as measured by the knowledge preserved—may be improved by increasing wayfinding demands judiciously [84]. Empirical evidence also shows that requiring certain types of spatial knowledge to be used during wayfinding facilitates their preservation [44, 51, 84, 98, 172, 243, 245]. While not predicted by the design-oriented model of navigation (or by the psychology-oriented model), these results are consistent with theories of active and experiential learning [150, 208]. The present work focuses on the constraints imposed on design by wayfinding cognition. Because of a dearth of efforts to facilitate searching and finding and the unique benefits and opportunities for doing so in electronic environments, these tasks will initially be used for design studies.

Navigational Design: A Taxonomy

In order to understand the relationship between navigational cognition and navigational design, it is not only necessary to examine navigation from a cognitive perspective, but also to examine navigational design from a design perspective. Navigational design may be conceived as the creation or manipulation of an environment or artifact intended to help (or hinder) navigational cognition. This depiction suggests two dimensions for describing navigational design: First, design or aspects of a design may be characterized by its *cognitive function*—the role it plays in cognition. Second, they may be characterized by *design element*—the type of elements that are manipulated by the design. Combining these orthogonal dimensions results in a *taxonomy of navigational design* that defines subsets of closely related design constraints (Figure 3).

Decomposition by Cognitive Function

The decomposition of navigation into the cognitive subtasks of locomotion, wayfinding, spatial knowledge preservation and information-gathering indicates that navigational cognition is concerned with three functions: controlling movement, reasoning and manipulating information about possible movement, and gathering environmental information about possible movement. This suggests decomposing navigational design into three functional subdomains: locomotional, informational and steering design.

Locomotional design is the design of what movement is possible, including defining what locations and paths are accessible, what the relationships among them are, and what the relationships are between these and movement. It dictates the concepts and elements over which the wayfinding and spatial knowledge preservation subtasks must operate, and determines what problems wayfinding must solve [214]. In essence, locomotional design determines *where* it is possible to go.

At least three different aspects of design can be manipulated separately to define locomotional design. The underlying "mechanical physics" define the rules that govern movement in the environment. For instance, a fundamental premise of hypertext is that it is only possible to move between two nodes that are "linked" and that movement from one node to another is atomic (i.e., uninterruptible and undirectable once begun) [54]. Movement in a document editor such as Microsoft® Word, in contrast, allows continuous movement in both horizontal and vertical dimensions of a two-dimensional plane.

Locomotional design can also be manipulated through locomotional "mechanism"—allowing the model of how movement is effected to dictate where it is possible to go. For instance, many windowing systems use scrollbars to effect movement. These limit freedom of movement to a single dimension, typically horizontal or vertical, within those allowed by the environmental physics. Finally, locomotional design can be manipulated directly, e.g., by imposing barriers to or conduits for movement explicitly. In hypertext, for example, all links (conduits for movement) must be defined explicitly and are peculiar to a particular network of nodes. Use of these conduits may be blocked explicitly depending on context, e.g., many websites require that the user have "cookies set" or that the user be logged in before movement to a particular page is permitted.

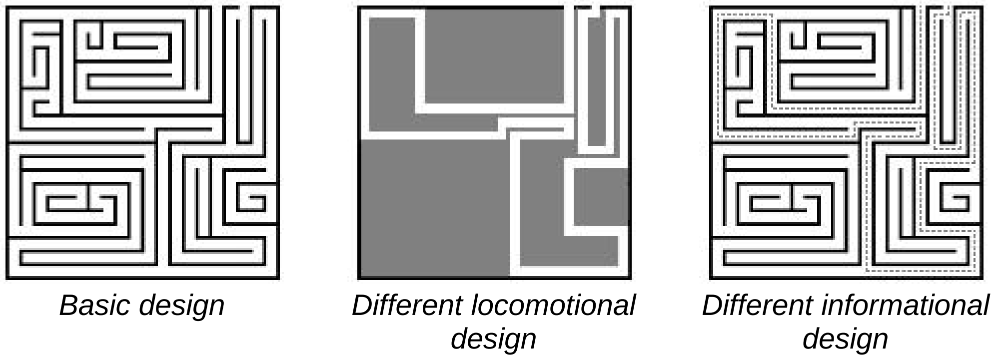
Informational design is the design of what information is available to the navigator. It determines, in part, what information about locations, paths and other relevant spatial attributes is available to wayfinding and spatial knowledge preservation, and dictates how much cognitive effort is necessary to process such information. Informational design, in contrast to locomotional design, does not change *where* it is possible to go, but rather changes what information is available, through perceptual means, *about* where it is possible to go.

Like locomotional design, informational design may be manipulated by manipulating different aspects of design. Design of information content of the environment determines what information is available. For instance, information might be added to an electronic document or website that shows patterns of access, presumably, indicating important or popular locations and paths through its contents [111, 279]. The design of information representation contributes to the navigators ability to perceive and interpret the information presented. For instance, if the patterns of access are indicated through color, the resulting information may not be available to a color-blind navigator. Or, if information is presented in Mandarin Chinese, it may not be available to an English navigator.

Whether and what information is available to a particular navigator is also affected by perceptual design—the design of perceptual apparatuses, sensory stimuli and their behavior. For example, design of the rules governing simulated perception in an electronic environment might allow lines of sight to “bend,” so that information obscured by “solid” objects can nonetheless be seen. Or aids might be added that augment the navigator’s simulated perception, e.g., simulating peripheral vision [229, 273]. Finally, the placement of information in the environment interacts with perceptual design to determine where the navigator must be, spatially, in order to perceive a particular piece of information.

Steering design is the design of the relationship between human action and movement within the environment, i.e., how movement is controlled. It determines what actions are required to change direction, speed, acceleration, etc.—defining the concepts and elements over which the cognitive subtask of locomotion operates. Whereas locomotional design determines *where* it is possible to go and informational design determines what information is available *about* where it is possible to go, steering design determines *what actions* are necessary to get there.

Note that the interpretation of the actions is considered part of locomotional design. For example if the steering design allows only one action, e.g., button click, this may be interpreted in a variety of ways resulting in different locomotional designs: a fixed “move forward” interpretation might preclude access to any “preceding” locations, “move forward, but reverse ‘forward’ direction if an obstacle is encountered” would reinstate such access if the world contains obstacles, while “move forward N+1 units (where N is the number of units moved in the previous move), then reverse ‘forward’ direction” reinstates such access even in an unbounded environment.



Note that all three designs require the same wayfinding solution.

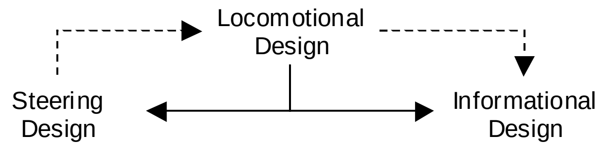
Figure 12 Manipulating locomotional and informational designs to change the problem posed or the information available.

Steering design may also be manipulated by manipulating a variety of aspects of design. These primarily concern the number and properties of the input device(s) used to convert human action to electronic signal. They include the selection of input device(s), (e.g., three-button mouse or voice input), interaction between devices (e.g., keyboard augmentation of mouse-button signals) and determination of what actions should be required to emit what signals (e.g., turning the "gain" up or down on a variable rate device).

The three maze designs shown Figure 12 illustrate the difference between manipulating locomotional and informational design to change the cognitive processing required to reach a wayfinding solution. All three designs require the same wayfinding solution, i.e., following the same path from beginning to end. The center design changes the difficulty of the wayfinding problem by manipulating where it is possible to go—locomotional design. The right design changes the difficulty of solving the wayfinding problem by changing the information available—informational design. Steering design might be manipulated in any of the designs, for instance, by making movement follow the direction of eye gaze or by requiring the wayfinder to "paint" the desired path in front of them with, for instance, a beam of light.

Relationships between Subdomains

Steering, locomotional and informational design affect different aspects of navigational cognition, but their design are not independent of each other (Figure 13).



Solid arrows show flow of design requirements, while dotted arrows show control of access to designed features during use.

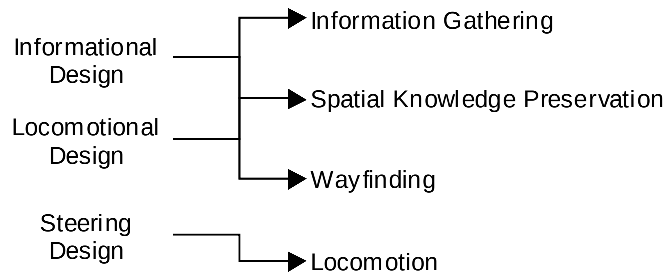
Figure 13 Relationships among subdomains of navigational design.

Locomotional design has implications for both steering and informational design: For steering design, it suggests the parameters of movement that may be controlled. For example, in the center design in Figure 12, the path of movement is dictated by the environment and the wayfinder need, in actuality, only control speed of movement. In the other two designs, however, the wayfinder must be able to control both direction and speed of movement. Steering design, in turn determines which aspects of the locomotional design are accessible during actual use—if the steering design only allows turns when there is an obstacle directly ahead, it does not matter if the locomotional design allows “mid-corridor” entries.

Locomotional design also affects informational design by suggesting what information is needed and where it is needed. For instance, in the right-most design in Figure 12, the locomotional design suggests providing information at critical turns. The informational design elects to provide information at critical turns and at all intervening locations. Conversely, locomotional design controls, in part, what informational design is accessible in actual use—the best-designed and most informative signs, maps and landmarks are useless if the road does not pass by them.

Relationships between Functional Subdomains and Cognitive Tasks

Not surprisingly, there is a clear correspondence between navigational subtasks and the three functional subdomains (Figure 13). Steering design affects performance of the locomotion subtask [38, 47, 219]. For instance, Card et al. [38] found that locomotional performance—in terms of speed as well as accuracy—in a text selection task (within a



Solid arrows show the tasks on whose performance a subdomain potentially has an effect.

Figure 14 Relationships between cognitive tasks and functional subdomains of navigational design.

single view) was significantly better with a mouse-based than with a joystick-based steering design [38].

Locomotional design directly affects wayfinding performance [25, 50, 57, 98, 174, 204, 214, 278]. For example, Best [25] showed that the number of locations in a building layout at which a decision is required directly affects how likely people are to lose their way in the building. It also determines, in part, what spatial information is preserved and how difficult spatial knowledge preservation is [73, 98, 205, 226, 233]. In a study by Rand, for instance, taxi drivers exhibited knowledge about how streets were interconnected while pilots, with experience of the same geographic location, exhibited greater knowledge of their relative spatial positions [226].

Informational design determines what information is gathered and how difficult it is to obtain [31, 93, 109, 285, 286]. Heft, for example, demonstrated that subjects opportunistically relied upon different types of information—e.g., geographical orientation (location of the sun), distal landmarks (visible mountain peaks) or artificial proximal cues (a pink flamingo at a critical turn)—depending on what was available, but that the type of information did not affect route learning performance [109].

However, other relationships between cognitive tasks and functional subdomains of navigational design are less obvious (Figure 14). Informational design affects wayfinding by controlling, in part, when information is available [25, 57, 81, 109, 210] and how much processing is required to make it useful [59, 194, 204, 230, 261, 285]. Wright, Hull and Lickorish, for instance, found that women[xx] who were given a hand-drawn map to navigate a hospital setting were slower to reach their destination, but retraced their steps less often to check that they were going in the right direction, than women who relied only on posted signage [285].

Locomotional design similarly affects information-gathering by determining, in part, when information is available [25, 28, 31, 44, 57]. Burns, for example, found that "saw sign too late" and "saw turn too late" were frequently reported causes of wayfinding errors while driving [31]. Although these may seem to be attributes of informational design, they are actually a property of the relationship between locomotional and informational design; if the road had been straight, the sign or turn might have been visible earlier. Steering design, alone among the three subtasks, appears to affect only one subtask directly.

Functional Subdomains Evident in Design Literature

Decomposition of navigational design by cognitive function was suggested by the decomposition of navigational cognition into subtasks. However, the literature describing design efforts to support navigation in electronic environments exhibits clear divisions that correspond to the boundaries between functional subdomains.

One body of work addresses steering design. One type of such work describes demands and attributes of different steering problems and techniques [1, 11, 18, 126, 177, 219, 264]. Accot and Zhai [1], for example, seek to develop mathematical models of the "steering difficulty" of trajectory-based tasks (e.g., selection from a submenu with a mouse) in order to predict locomotional task performance. Igarashi et al. [126], describe a technique to support such tasks in virtual environments that allows the user to "draw" the desired trajectory rather than requiring them to exert continuous directional control (the system projects the drawn path into the 3D environment, then computes and directs movement along an appropriate trajectory). Another type of work related to steering design focuses on properties of devices used to control movement [10, 13, 38, 176, 178],

[xx] All subjects were female.

e.g., comparing the effectiveness of different devices for a particular task (mouse versus joystick, for example) [38], or developing a taxonomy for describing input devices based on the translations between physical action and electronic signal a device offers [178].

A smaller body of literature addresses locomotional design. One type of effort in this area compares different arrangements of locations and paths between them [29, 50, 253]. For example, Chimera and Shneiderman [50] compared two presentations of a table of contents, one in which all items were presented simultaneously as a list (i.e., all items were accessible either directly or directly after scrolling) and one in which items were presented according to their hierarchical structure (i.e., in order to reach a subitem, its containing item must be accessed first). The hierarchical presentation produced faster performance times.

A different type of effort focuses on techniques for adapting the available locations and paths dynamically [56, 78], for instance, hiding or revealing hypertext links in accordance with a student's assessed level of understanding. Other efforts seek to define locations and paths dynamically and/or algorithmically [85, 104, 136]. For example, Galyean [85] proposes a means of defining a path through a virtual museum by defining paths of movement in terms of spatial relationships to objects in the environment, but allowing users full control of movement within paths.

The majority of efforts to support navigational design addresses informational design. One type of such effort focuses on different techniques for presenting information [18, 24, 59, 61, 121, 166, 230, 279, 287]. Darken and Sibert [59], for instance, examined how different informational tools affected searching behavior in a virtual world, e.g., providing a continuous readout of current position in absolute coordinates, augmenting the environment with artificial landmark objects or providing an overview map that indicates current location. Other efforts focus on properties of the information provided [81, 93, 127, 275]. For instance, Furnas [81], defines a concept of "residue"—information about a remote location or object that allows a navigator to decide which action to take to move toward that location—and describes the types of residue that must be provided if error-free navigation based only on perceptually available information is to be possible.

Very few efforts to develop navigational design span multiple subdomains. Pausch et al. [216] offer an intriguing example in so-called “World in Miniature” (WIM) navigation. This technique offers the navigator in a virtual world a “hand-held” miniature view of the environment (informational design). The navigator may control movement by “flying into” a location in this miniature world (steering design), which then becomes the current immersive environment and a new miniature appears. Since the navigator may “fly into” any portion of the miniature world, they are no longer constrained to movement between contiguous locations in the environment (i.e., the locomotional design has also been altered). History-based designs that show where the user has been and, simultaneously, provide a means for returning there [78, 279] span both locomotional and informational design.

These examples show that decomposition by cognitive function reflects genuine divisions in navigational design. They also provide a means for detecting aspects of navigational design that are neglected in any particular design, suggesting directions in which it might enhanced.

Decomposition by Design Element

In a seminal work in the field of ecological psychology (consideration of psychology with respect to its environmental context) entitled *The Ecological Approach to Visual Perception* [91], James J. Gibson introduced the concept of *affordances*. This concept captures the dependency of opportunities for action on properties of both an active agent and an environment of action. For example, a moonless night affords seeing to an owl but not to a human, while trees afford climbing to many humans but not to most owls. In other words, an affordance is what a particular environment or object enables a particular agent to do[xxi].

[xxi] Norman [198] popularized the term “affordance,” but used it to mean the user’s apperception of what a particular environment or object enables them to do. This definition encourages the confounding of *what* a design enables a user to do (the ends of the design) with *how* it makes the user aware of what they can do (the means of the

Most user interface design, including navigational design, is the design of affordances. Consequently, it can be approached in two ways: The design can manipulate properties of the environment or it can augment the capabilities of the agent. For example, human seeing on a moonless night can be enabled either by adding streetlamps to the environment or by augmenting the human's vision with a night scope. This suggests decomposing user interface designs according to whether the environment or user capabilities are manipulated.

Environmental design is the design of environmental properties. Environmental design may be independent of the capabilities of the user, although intentionally designed features may have been adapted to users' natural capabilities—e.g., providing streetlamps that emit light in the human-visible spectrum. *Prosthetic design* is the design of aids that augment the natural capabilities of the user. Prosthetic design is specifically tailored to make use of particular properties of an environment. For example, the environmental "design" of the earth includes a magnetic field that is not directly perceptible by humans (although it is by other species [283]), but human perception can be augmented with prosthetic devices, such as a compass, that allow them to "perceive" magnetic fields. Of course, some designs may employ both approaches, e.g., broadcasting radio signals into the air and providing people with receivers in order to "hear" them.

In the context of navigational design, environmental design is the design of opportunities for movement and information offered by the environment, while prosthetic design is the design of individual navigational devices. While this distinction is generally clear in the physical world, it is easily blurred in electronic environments. Electronic environments are, inherently, themselves prosthetic designs, so what is environmental design and what is prosthetic design depends on what is considered the environment of action and what is considered augmentative tools. For example, to the designer of a website, the information space comprising the actual web pages and their contents is the environment of action and navigational aids such as history lists or bookmarking

---

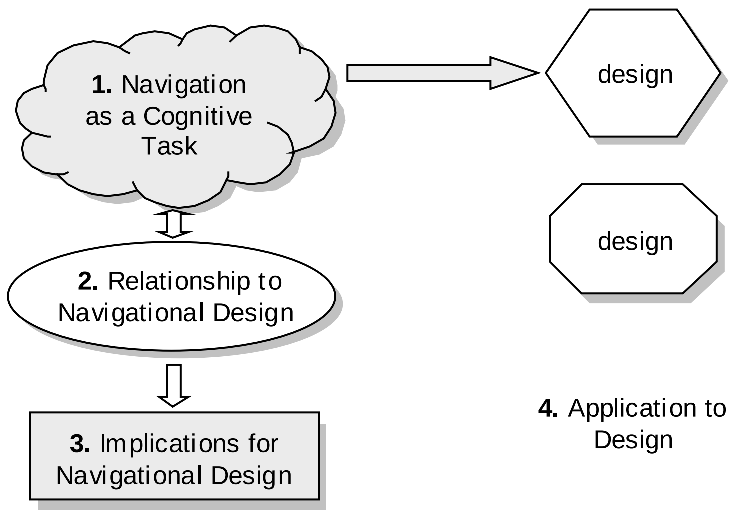
design). While Norman's definition is the more commonly understood in the human-computer interaction community, the present work retains Gibson's definition in order to keep this distinction clear.

capabilities [24, 78, 195, 279] are prosthetic aids. To the designer of the web browser, the interaction space, including history lists and bookmarking capabilities, is the environment of action, and operating system facilities such as those that allow the user to switch between applications are prosthetic aids.

In general, prosthetic design can be thought of as design that travels “with” the navigator, while environmental design is fixed with respect to the environment and so varies with the navigator’s location. For example, environmental locomotional design may manipulate the properties of movement in the environment [16, 218, 255], constrain movement dynamically [85, 104], arrange the layout of the environment [50, 127, 257, 275] or rearrange the layout dynamically [29, 56]. In these cases, how the design enables the user to move depends on their location. In contrast, prosthetic locomotional design may augment the paths offered by the environment, for example, with short-cuts that provide direct access to special locations [24, 78, 195, 279]. Some designs are generic and can be employed as either environmental or prosthetic design, e.g., different ways of defining object-relative movement [126, 177] that could define movement or augment existing movement in an environment.

Subdomains of Navigational Design Reflected in Design Literature

The two decompositions of navigational design—by cognitive function and by design element—are orthogonal to each other, and define a taxonomy comprising six subdomains. As with decomposition by cognitive function alone, decomposition along both dimensions is reflected in the literature describing design efforts to support navigation in electronic environments. All of the steering design efforts described earlier (*Functional Subdomains Evident in Design Literature*, p. 73) address different types of prosthetic design, most notably, input devices. Mine et al. [186] offer a singular effort to address steering through environmental design, by configuring a virtual environment to detect and interpret the user’s physical movements in order to control virtual movement, that is, separating the sensors that detect movement from the user. All of the efforts described that support locomotional design are aimed at environmental design. No efforts seem to have been directed at prosthetic locomotional design.



Shading indicates which steps of the process have been explored by others.

The lack of containing boxes indicates that none have addressed the need for a cascading process that converts knowledge systematically.

Figure 15 Aspects of the design knowledge development process for understanding navigation as a problem in design that have been the subject of other research.

Only in informational design have efforts been aimed at prosthetic design—e.g., environmental overviews or maps—as well as at environmental design—e.g., augmenting the environment with landmarks. It is interesting to note that explicit design principles or guidelines have been developed for the subdomain of environmental informational design [81, 127, 275], alone of the six subdomains.

Overall, prosthetic design has received substantially more attention than environmental design, in the context of navigational design, and environmental steering and locomotional designs have been particularly neglected. This distribution of attention is not surprising as it reflects design opportunities offered by physical environments. However, it likely causes opportunities offered by electronic environments to be overlooked. Because of the lack of attention to the subdomain of environmental locomotional design and the opportunities offered by electronic environments for reducing the need for prosthetic and informational design through environmental locomotional design, this dissertation focuses on this subdomain.

Other Efforts Aimed at Supporting Navigational Design

The design knowledge development process for understanding of navigation as a problem in design comprises four steps (Figure 2, p. 10): (1) Understanding navigation as cognitive task, (2) Understanding the relationships between navigational cognition and navigational design, (3) Deriving implications for design from these relationships, and (4) Understanding how to apply this knowledge to design. Most other efforts aimed at supporting navigational design focus on only one of the four (Figure 15). First, efforts have been made to describe navigation as a cognitive task [48, 256]. Second, knowledge of specific aspects of navigational cognition has been used to derive implications for design [81, 181, 275 and to develop formal models for design evaluation [25, 57, 101, 174, 205]. Third, knowledge of specific aspects of navigational cognition has been applied directly to particular design situations [43, 127, 257]. Only the lifelong work of Romedi Passini [213] and the work of Mary S. McCormick [181] address multiple steps systematically.

Describing Navigation as Cognitive Task

Spence: Navigation is Spatial Knowledge Preservation

Spence [256] proposes a conceptual model of navigational cognition for the purpose of supporting navigational design. He explicitly defines "navigation" as "*the creation and interpretation of an internal* [i.e., mental] *model*" [256, p. 920]. This model details an iterative process comprising four cognitive behaviors: *browsing* (perceptual information-gathering), *modeling* (cognitive-map formation), *interpreting* (attributing meaning to items and relationships represented in the cognitive map) and *formulation of a browsing strategy* (decision-making or planning about ensuing browsing behavior). This model is derived from theoretical consideration of the problems solved during navigation combined with models of general cognition. Spence uses his model to speculate about key characteristics of the four navigational behaviors and describe how different designs facilitate them.

Spence’s definition of navigation coincides with the present definitions of information-gathering and spatial knowledge preservation. His model provides a potential starting point for an exploration of the constraints imposed by these tasks. However, it does not have a direct bearing on the present effort to understand the constraints imposed by wayfinding.

Chen and Stanney: Prosthetic Informational Design

Chen and Stanney [48] propose a model of “wayfinding” in virtual environments that corresponds to the commonly assumed psychology-oriented model of navigation (Figure 11). They explicitly include *cognitive mapping* and *decision-making* as essential subtasks and indicate that information-gathering is a separate constituent component. They define “navigation” as *decision-execution*, that is, as what is here called locomotion. Their model is based on evidence from the literature on spatial cognition and cognitive mapping and the empirical work by Passini [213, 212, 211, 210] (cf. *Romedi Passini: Wayfinding in Architecture*, p. 87) on navigational problem-solving and decision-making in physical environments. Chen and Stanney use the model to propose a taxonomy of “navigational tools” that classifies prosthetic informational designs into five categories based on the type of information they provide (position, orientation, past movement, environmental context and route guidance).

While this model reinforces the design-oriented model of navigation developed here, at least insofar as the decomposition into subtasks, the work does not provide any understanding of the relationship between navigational cognition and environmental design. It also does not provide any insights into the implications of the former on the latter.

Burns: Errors in Wayfinding

Burns [31] explicitly excludes strategic planning from his consideration of “wayfinding.” His model comprises the subtasks of *perception*, *situation assessment* and *decision-making*. Situation assessment includes the spatial problem-solving involved in predicting what routes are available, but does not include strategic planning about how to choose between them or obtain further information. He explicitly regards cognitive mapping as separate from wayfinding, but acknowledges cognitive maps as a source of information. The relationships among cognitive subtasks in Burns' model are the same as those in the design-oriented model of navigation developed here. Burns does not explain the derivation of his model, but states that it is motivated by descriptions of wayfinding in the driving[xxii] context and general theories of wayfinding, combined with models of human information-processing.

Burns uses his model to develop a classification of wayfinding errors according to where in the process an error occurs and what the underlying cause of the error is. This classification is derived from analysis of a survey of the wayfinding experiences of 5000 drivers. Interestingly, of the five categories of causes of error reported, three concern the navigational design: Insufficient or poor signage or other information, Complexities of particular locations (intersections, one-way roads, etc.) and Situational conditions (e.g., poor visibility or heavy traffic). These divisions reflect and support the decomposition of navigational design into informational and locomotional aspects. A fourth category, Error, which subsumes simple steering errors such as wrong lane or wrong turn[xxiii], supports the separation of steering from other aspects of design. (The fifth category, Individual error, comprises driver-related causes, such as inattention or poor sense of direction, and is independent of navigational design.)

With the proviso that strategic planning is not considered and that problem-solving is therefore omitted, Burns' model is identical to the design-oriented model of navigation offered here. The results of his survey provide significant details about the relationship between wayfinding cognition and navigational design that will be discussed in detail in Chapter 3 (*Generating and Selecting Options*, p. 134).

[xxii] I.e., driving an automobile in the physical world.

[xxiii] These might also represent strategic planning errors, but Burns does not consider this level, so does not allow such classification. It is not clear whether his questionnaire prevented such confounding.

Conclusions

The models of Spence, Chen and Stanney, and Burns draw, in varying degrees, on empirical evidence regarding navigational cognition. Neither Spence nor Chen and Stanney attempt to relate cognition to design or derive implications for design systematically. Spence postulates abstract properties of design that might affect spatial knowledge preservation, but does not link these properties to actual design elements. Chen and Stanney consider only a single subdomain of design, and provide no specific implications for design even within this subdomain. Burns seeks to expose relationships between cognition and design, but does not derive implications for design. Thus, none of these efforts provides the direct support for design generation or the articulation of design constraints that are the goals of the present work.

Deriving Implications for Design

In contrast to efforts that develop models of navigational cognition, but fail to derive implications for design, other efforts derive implications from design, but do so from limited bodies of knowledge. It is thus often not clear whether the implications described represent variant or invariant constraints or to what types of navigational design problems they apply. These efforts explicitly aim to support either design generation or design evaluation, typically resulting in either principles or guidelines for design generation or computational models for design evaluation. Both approaches identify important design constraints, but the latter is limited to constraints that can be expressed quantitatively.

Design Principles and Guidelines

Lynch: Elements of Cognitive Maps

The work of Kevin Lynch [172], aimed at supporting urban design, was seminal in understanding the structure of cognitive maps of physical environments. He conducted an examination of the conceptual understandings that 60 residents of three different American cities held of the spatial structure of their respective cities. He found that five elements were sufficient to describe their mental representations: *landmarks, nodes, districts, paths* and *edges*. The first three can be viewed as locations at different levels of scale. Landmarks are spatial reference points that are not entered. Nodes are small regions defined by a particular object or location of interest. Districts are coherent geographical regions defined by elements that share some particular characteristic. The other two elements are linear and are defined with respect to movement. Paths are lines along which movement is possible. Edges are boundaries that obstruct movement.

Lynch defines two characteristics of city design that facilitate the development of cognitive maps. *Legibility* is “the ease with which its [the visual design’s] parts can be recognized and organized into a coherent pattern” [172, p. 2]. *Imageability* is “that quality in a physical object which gives it a high probability of evoking a strong image in any given observer” [Ibid., p. 9]. He then defines a set of perceptual properties of the five elements that contribute to a design’s legibility and imageability. These properties reflect constraints imposed by the cognition of spatial knowledge preservation on environmental informational design and, as such, do not apply directly to the present work, which is focused on environmental locomotional design. However, Lynch’s work has inspired several efforts to develop design principles or guidelines for the design of electronic environments, and some aspects of his work will also be used in the present work. These are discussed in detail in Chapter 3 (*Environmental Elements in Mental Representations*, p. 121).

Vinson: Landmarks in Virtual Environments

Vinson [275] derives a set of guidelines for incorporating Lynch’s five elements into a Virtual Environment using evidence from the literature on cognitive mapping. These guidelines represent internal constraints imposed by the use of the five elements as visual reference points on their visual design and relationships, e.g., “Guideline 7: The sides of a landmark must differ from each other” [275, p. 281]. Vinson does not discuss how the guidelines are to be applied in actual design situations, and does not provide any means of resolving conflicts among them. As they represent internal constraints and directly reflect constraints of physical designs, they are primarily applicable to design situations that seek to simulate physical environments and in which supporting spatial knowledge preservation is a primary design goal.

Furnas: View-Based Navigation

The work by Lynch and the work derived from it focus on cognitive maps and cognitive mapping. In contrast, Furnas [81] focuses on wayfinding. He articulates a set of requirements that must be met for *view-based navigation* to succeed. In view-based navigation, the goal of the navigator is to find a shortest path between two locations, without error, using only perceptual information. Furnas derives his requirements from human information-processing theory. These requirements represent external constraints imposed by human information-processing on informational design, arguing, for example, that, at each location at which the navigator must make a decision, information must be provided from which the navigator can infer, for any given destination, which choice leads to the destination via a shortest path.

Woods: Visual Momentum

Woods [284] also draws on theories of human perception and information-processing, but seeks to support information-gathering. He defines the concept of *visual momentum* as “A measure of the user’s ability to extract and integrate information across displays, in other words, a measure of the distribution of attention” [284, p. 231]. He proposes a set of design principles for design of a visual display that increase visual momentum. These represent internal constraints on the relationships between displays shown in succession, e.g., “Another technique to join together successive views is to provide across-display landmarks” [284, p. 236].

Conclusions

It is interesting to note that most, if not all, prior efforts to provide principles or guidelines to support navigational design of electronic environments have focused on environmental informational design. A focus on environmental design is understandable since prosthetic design depends on environmental characteristics. However, the lack of attention to locomotional design seems to stem from a reliance on understanding of navigation developed in the physical world and reveals a neglect of the possibilities offered by electronic environments.

Implications for Design Evaluation

Efforts to support design evaluation are predominantly aimed at evaluating wayfinding difficulty of designed physical environments, and primarily focus on environmental locomotional design, using one of two approaches. The first approach is to develop mathematical formulae that simulate or predict wayfinding difficulty from environmental properties. These efforts typically aim to predict performance under specific circumstances that allow explicit assumptions about the navigator's prior knowledge, for example, emergency evacuations [174], airports [57] or wholly unfamiliar buildings [25, 204]. The other approach is similar, except that it results in computational models and seeks to predict wayfinding behavior (i.e., sequence of decisions) [101, 205] from environmental properties. Both approaches develop evaluation criteria that may provide insights into constraints between navigation and cognition. These efforts and their specific findings will be discussed in Chapter 3 (*Mathematical and Computational Models of Wayfinding*, p. 115).

Applying Knowledge to Specific Design Situations (Point Designs)

Other efforts to use psychological knowledge to support navigational design have sought to apply knowledge directly to particular design situations, that is, to produce an actual design rather than ways of supporting the design process[xxiv]. Such efforts generally draw on isolated pieces of understanding, either of navigational cognition or of the relationships between cognition and environment, and do not seek to formalize the underlying understandings or constraints or to detail their implications for design.

Perlin and Fox [218] used attributes of visuo-spatial cognition to develop a novel environmental design in which users can move through scale. Bernstein [24] and Darken

---

[xxiv] Such designs are examples of *point designs*, designs that explore particular points in a design space.

and Sibert [59] used knowledge of perceptual strategies for maintaining an understanding of current position and orientation to develop and test prosthetic informational designs. Such work, of course, represents the application of particular design constraints and can serve to illustrate these. However, these efforts are too isolated to inform a systematic set of constraints.

Understanding Wayfinding as a Problem in Physical Design

The efforts discussed in the previous sections all focused on only one of the four steps of the design knowledge development process for understanding navigation as a problem in design. The works of McCormick [181] and Passini [214, 213, 212, 211, 210] are similar to the present work in that they progress systematically through several steps. Both efforts focus on architectural design in support of wayfinding. Details of their findings will be discussed in Chapter 3 (*passim*), but the approaches and intent resemble that of the present work and are discussed here.

Mary S. McCormick: Recommendations for Wayfinding Design

As part of a PhD in Architecture, Mary S. McCormick conducted an observational study of 5000 patients and visitors to a major health-care facility in order to generate design guidelines for expansion of that facility [181]. Starting with evidence reported in the literature on the relationship between environmental design and wayfinding[xxv] cognition, she selected a small set of presumed key design elements—for instance, intersections—and then observed the wayfinding behavior of visitors at a set of locations representing those key elements.

She then analyzed how different properties of the environmental design correlated with differences in observed behavior, determining, for instance, that “Vistas can enhance people’s natural tendency to move toward large, open spaces” [181, p. 325]. Based on

[xxv] McCormick uses “wayfinding” in the same sense as used here—to denote the spatial problem-solving and decision-making component of navigation—although she does not formally distinguish it from information-gathering and spatial knowledge preservation.

these correlations, she formulated a set of specific design recommendations, e.g., "Main routes and public areas should be larger in volume—taller, wider and deeper—than secondary routes" [Ibid., p. 313]. These recommendations link wayfinding performance to specific properties of elements of both environmental locomotional and environmental informational design.

In contrast to the present work, McCormick does not base her analysis on a model of wayfinding as a cognitive task. Rather, she reviews architectural forms of prehistoric and isolated societies in order to develop an understanding of how the basic cognitive needs of wayfinding manifest in physical design. She then combines this understanding with evidence from the literature on perception and spatial cognition to relate wayfinding cognition to key design elements. Like the present work, she then seeks to develop an understanding of the relationship between environmental design and wayfinding performance, although she draws on personally-conducted observation rather than analysis of existing empirical evidence. Thus, McCormick applies the second and third steps of the process used here to identify external constraints on environmental design of physical environments.

Romedi Passini: Wayfinding in Architecture

Romedi Passini [214, 213, 212, 211, 210], like McCormick, develops an understanding of the relationships between wayfinding[xxvi] cognition and environmental design and uses it to articulate implications for architectural design [213]. He, however, first develops a detailed model of wayfinding cognition based on think-aloud data collected during personally-conducted observations of the wayfinding behavior of individuals [212, 211]. He uses these same data to identify elements and properties of environmental design that are sources of major wayfinding difficulties, in essence, developing a model of environmental design.

[xxvi] Passini defines "wayfinding" as spatial problem-solving and decision-making, but includes information-gathering as a subtask [211].

He combines these understandings to articulate a “Guideline to Wayfinding Design” [213]. This process details seven steps (four related to problem analysis and three to design generation) for developing environmental informational design. This process implicitly embeds a set of external constraints imposed by wayfinding cognition on physical design, and, simultaneously, details their application to design. Consequently, Passini’s work follows the process outlined in Figure 2, applying all four steps. Like McCormick’s work, Passini’s work differs from the present effort in that it is based on direct observation rather than a consolidation of existing knowledge and also in that it is directed toward physical design.

Note that Passini’s “Guideline” focuses on environmental informational design and takes the locomotional design as given. For instance, "[at each location where the user must make a choice] plan the supportive environmental information that will allow the user of a setting to find the desired routes to a destination as specified above” [213, p. 177]. Interestingly, in applying the first and second steps, he includes information about the relationships between wayfinding cognition and environmental locomotional design, but, likely because of the focus on physical environments, he does not discuss their implications for design until much later work [214].

Similar Approaches to Supporting Design

The design knowledge development process combines several approaches used in other efforts to support design. Identifying and organizing knowledge about some class of problems in order to support solving those problems is analogous to the approach of Domain Analysis [8, 9, 223] used in software engineering for the design of application frameworks[xxvii]. However, where Domain Analysis bases domains on families of applications [8, 79, 223], the present work uses a cognitive task to define a domain of analysis.

[xxvii] Collections of associated software components used by developers to help construct software applications.

The approach of analyzing a cognitive task is not unknown to human-computer interaction. Methodologies for Cognitive Task Analysis [238] aim at helping designers analyze unspecified tasks during design. The present work, in contrast, seeks to analyze a specific task in advance of actual design. This could be viewed as an example of cognitive task analysis in what might be termed “proto-design.”

Other efforts to aid proto-design of user interfaces have also drawn on existing psychological knowledge. However, these have largely focused on design evaluation and have developed models of human performance on fundamental cognitive tasks, e.g., the well-known Model Human Processor [42]. These approaches link cognitive tasks to perceptual and cognitive mechanisms—such as working and long-term memory—so that designs may be evaluated in terms of the cost of task performance. They require tasks to be specified at a level of detail that is dependent on the particulars of a design, and provide no assistance in generating that design. The present work, in contrast, seeks to link performance on specific cognitive tasks to specific environmental phenomena in order to provide generative information.

In contrast to other efforts to provide generative information, the design knowledge development proposed here describes a means of deriving design knowledge from other types of knowledge and, thus, allows existing empirical evidence to be used. Other efforts in the context of navigational design, offer examples of deriving design knowledge from personally conducted empirical studies [211, 213, 181] and from cognitive theory [81], but do not describe a process for doing so. Using existing empirical evidence capitalizes on decades of scientific research, ensures generality of the resulting design implications, and helps guard against confounding knowledge that applies only to a few designs with knowledge that applies to a broad range of designs.

Summary

This chapter presented evidence to support the assumption that explicit articulation of design constraints can be expected to aid designers in the analytical and generative phases of design, and identified invariant, radical, external, user constraints as being the present category of interest. It then examined how other efforts have used understanding or knowledge of constraints to support design.

Turning to the identification of constraints in navigational design, it developed two general conceptual frameworks for understanding navigation as a cognitive task (the design-oriented model of navigation) and navigational design as a design problem (the taxonomy of navigational design), respectively, and outlined how design constraints might be identified from relationships between them. The development of these frameworks introduced new concepts and new vocabularies. These were used to examine other research efforts that articulate similar frameworks or derive design constraints from similar information. The majority of other efforts sought to consolidate existing understandings and consequently focused on subsets—single components—of the problem of understanding navigation as a problem in design. This dissertation, in contrast, seeks to go beyond existing understandings to develop new understanding, developing “new words and concepts for the alphabet of understanding navigational design.”

The next step is to explore the use of this new “alphabet.” The design-oriented model of navigation specifies four cognitive subtasks of navigation, and the taxonomy of navigational design specifies six subdomains that potentially affect their execution. This results in the decomposition of the navigational design problem into twenty-four subproblems (Figure 3), each of which potentially represents a complex of related constraints. The following chapters explore the articulation and application to design of one set of constraints—the constraints imposed by wayfinding cognition on environmental locomotional design—that is, to explore what lies beyond the “Z.”

CHAPTER 3
Wayfinding Cognition and Environmental Locomotional Design

And IF *you go in, should you turn left or right...*
or right-and-three-quarters? Or, maybe, not quite?
Or go around back and sneak in from behind?
Simple it's not, I'm afraid you will find,
for a mind-maker-upper to make up his mind.
Dr. Seuss, *Oh, the Places You'll Go!*[xxviii]

Intuition and experience suggest that navigational design plays a key role in determining how simple it is "for a mind-maker-upper to make up his mind" (or not). That is, it is probably easier to decide whether to turn "left or right" than it is to decide whether to turn "left or right... or right-and-three-quarters. Or, maybe, not quite." Psychological evidence confirms this intuition and provides indications of what specific properties of navigational design affect navigational cognition. This chapter begins the process of understanding wayfinding as a problem in environmental locomotional design—a subproblem of understanding navigation as a problem in design—by examining existing empirical evidence for relationships between wayfinding and environmental locomotional design.

The cognitive subtask of wayfinding was selected because it is inherent to navigational cognition but design to support it has not received commensurate attention. The design subdomain of environmental locomotional design was selected because it defines the need for informational or prosthetic design and dictates what problems wayfinding must address.

---

xxviii [242] Reprinted from *Oh, the Places You'll Go!*, Dr. Seuss, p. 23, ©1990, with permission from Random House Publications.

For example, if the environmental locomotional design offers options to turn “left,” “right,” “right-and-three-quarters” (“or, maybe, not quite”), or “go around back and sneak in from behind,” the navigator must make up their mind among these. The informational design must—assuming ease of wayfinding is a design goal—provide information about the presence of these options and where they might lead. However, if turning “left,” “right,” “right-and-three-quarters” (or, “maybe, not quite”) ultimately have the same effect, perhaps these options can be replaced with a single “go in” (perhaps a right-and-one-quarter turn) option. The “mind-maker-upper” must then only choose between “go in” and “sneak in from behind.” There is also then no need for “left” and “right” signage and, potentially, no need for prosthetics to detect “left” and “right” options and their attendant signage.

Note that the distinction between locomotional design—what movement is made possible—and informational design—what information is made available—is not generally made clear in the psychological literature, and, consequently, may be difficult to keep in mind when examining this literature. It is, however, important to design—particularly to design of electronic environments where the two may be manipulated dynamically and independently of each other. For instance, the “left,” “right,” and “right-and-three-quarters” options may be collapsed into one either by limiting movement to one “go in” path or by showing the wayfinder only one “go in” path. The former (locomotional design) solution may eliminate the need for informational design, while the latter (informational design) solution leaves open the possibility for the wayfinder to select an unlabeled option (either intentionally or by accident).

The process employed to understand wayfinding as a problem in environmental locomotional design (Figure 4, p. 14), is the same as that proposed for the general problem of understanding navigation as a problem in design (Figure 2, p. 10), but with a limited scope at each step. The reduced scope allows each step to be pursued to the level of detail needed to identify specific design constraints. This chapter completes the first two steps of the method, developing a model of wayfinding as a cognitive task and describing the relationships between wayfinding and environmental locomotional design, as made evident by existing empirical evidence. The third and fourth steps of the method are completed in the following chapter.

The first step of the design knowledge development process applied to wayfinding develops a *design-oriented model of wayfinding* as a cognitive task. As discussed in Chapter 2 (*Behavior, Cognition and Design Constraints*, p. 46), such a model should be derived from actual behavior and must dissociate tasks induced by a particular environment from those that result from fundamental cognition, if it is to serve in the derivation of fundamental constraints. Several models outlining a gross cognitive process of wayfinding have been offered [31, 48, 211], but none offers details concerning how the process is accomplished and only that of Passini [211] is demonstrably based on empirical evidence.

Fortunately, wayfinding is commonly seen [31, 48, 97, 98, 174, 201, 211, 258, 277], and here accepted, as a process of problem-solving and decision-making, and several models of the cognition of general problem-solving and decision-making are available. The models to be considered here—Problem-Space Search [193, 250, 249], Naturalistic Decision-Making [146, 289], and Reflective Problem-Solving [235]—are all based on empirical evidence of actual problem-solving and decision-making behavior. They are intended to generalize across environments, and so either explicitly seek to describe fundamental cognitive tasks—independent of both problem specifics and environmental details—or to identify contextual attributes that affect problem-solving and decision-making. They can thus be used directly for the present purposes.

While models of general problem-solving and decision-making meet the desired requirements, they are models of a general task and do not provide the necessary details about wayfinding. This detail is, however, to be found in the literature presenting empirical evidence of cognitive wayfinding tasks and behaviors. Thus, the design-oriented model of wayfinding is formed by combining these. It comprises four subtasks: *path-identification* (developing a mental representation of locomotional options), *route-prediction* (predicting which environmental paths meet wayfinding goals), *route-selection* (selecting from among the viable options) and *route-following* (monitoring locomotion along the selected path).

The design-oriented model of wayfinding guides the second step of the design knowledge development process—describing the relationships between wayfinding cognition and environmental locomotional design. This step analyzes the empirical evidence surrounding wayfinding cognition in order to identify specific elements of environmental locomotional design that affect wayfinding and detail their relationships to wayfinding performance. This results in the identification of four key elements. The most fundamental of these is the *locomotional structure*—the set of locations and paths that are available to the wayfinder. This structure determines the nature and complexity of wayfinding problems. The remaining three elements pertain to relationships between this structure and the superordinate task, other aspects of the environmental design and the steering design, respectively. They control, among other things, the cognitive effort required and resources available for wayfinding problem-solving and decision-making.

These first two steps—developing a design-oriented model of wayfinding as a cognitive task and understanding the relationships between this task and environmental locomotional design—both entail analyzing and organizing psychological knowledge. The ensuing two steps, described in the next chapter, use this information to develop design knowledge.

Wayfinding as a Cognitive Task

Although many efforts consider wayfinding[xxix] a spatial problem-solving and decision-making process [31, 48, 51, 81, 87, 174, 182, 201, 212, 210], none presents an explicit model of the process itself. Most models offered like that of Burns [31] or that of Chen and Stanney [48] include a step labeled “Decision” or “Decision Making Process,” but do not elucidate this further. Two efforts, those of Passini [211, 213] and of Stern and Portugali [258], illuminate aspects of the process, but do not provide an actual process model.

[xxix] For the remainder of the present work, navigational terms will be used as defined in Chapter 2, regardless of the terms originally used by authors in work cited.

Passini [211, 213] describes wayfinding as a sequence of hierarchically structured decisions, describable by so-called “decision-plans.” Decision-plans detail the goals, subgoals and behavioral actions taken during a given act of wayfinding. For example, he illustrates [213, p. 65] (drawing from observational data) how a decision to “go to Turtle Atoll” resulted in three further decisions: “to sail to Coral Reef,” and then “to follow [Coral] Reef to Big Dip” and then “to home on Turtle Atoll.” The second of these resulted in two further decisions: “to set canoe on new course” and then “to sail according to Reef outline.” Decisions are decomposed in this manner until they relate simple behavioral actions such as “turn rudder to the right.” Decision-plans thus describe the products of a wayfinding process, but not the actual process.

Stern and Portugali [258], in contrast, develop a model of factors that may affect the wayfinding process, using Decision Field Theory. This model incorporates factors such as the information available, the wayfinder’s “global” experience (of the given type of environment) and their “specific” experience (i.e., experience in the given environment). It models how the information might affect a problem-solving and decision-making process, but, again, is not a model of the actual process.

Consequently, it is necessary to develop a model of the wayfinding problem-solving and decision-making process. Fortunately, such a model need not be constructed solely from empirical evidence of wayfinding behavior but can be based on models of general problem-solving and decision-making.

General Problem-Solving and Decision-Making

Classical decision theory offers a variety of prescriptive models of optimal decision-making based on mathematical notions of uncertainty, risk and potential benefit [17, 250]. These so-called “rational choice” models describe different means by which a decision-maker, acting in a consistent, rational manner under perfect conditions, can make optimal decisions—describing ideal behavior. They have been the basis for much work in economics, mathematics, operations research, artificial intelligence, cognitive science and other disciplines. They have also—perhaps unintentionally[xxx]—become confounded with models describing the psychology of human problem-solving and decision-making. That is, in addition to describing mathematically ideal behavior, classical decision theory has come to be perceived, by some, as describing perfect human behavior. Rational choice models of problem-solving and decision-making, however, generally predict actual human behavior poorly [17, 146, 235, 250].

Although a variety of models of problem-solving and decision-making that account for actual behavior exists, there is no consensus on a single model. For the purposes of this dissertation, three models have been selected as a representative spectrum of current understanding. *Problem-Space Search* [193, 250, 249] takes an information-theoretic approach and describes an information-processing system that exhibits the same characteristics as humans solving puzzle-like problems in laboratory settings. *Naturalistic Decision-Making* [146, 289] reflects an ethnographic approach and describes expert problem-solving and decision-making in dynamic situations. *Reflective Problem-Solving* [235] is based on case studies drawn from different planning professions (e.g., architecture, urban planning and psychotherapy) and focuses on elucidating the role of the external problem setting in problem-solving and decision-making. Note that although two of these models purport to be models of "problem-solving" and one of "decision-making," each comprises both tasks.

These three models differ in many details, reflecting, perhaps, the different types of problems studied and the contexts in which they were studied. However, at a general level, they exhibit striking similarities, suggesting that they may be models of different problem-solving and decision-making strategies rather than different models of problem-solving and decision-making. The most important similarity, for the present purposes, is that they outline very similar processes. These can be reconciled as a single common process, which is presumed to represent the fundamental cognitive task of problem-solving and decision-making. This process comprises four subtasks: developing a mental

---

[xxx] Beach and Lipshitz [17] speculate that the appropriation of terms commonly used to describe observed behavior for specifying classical decision theory has caused a misperception that the theory was intended to describe actual behavior.

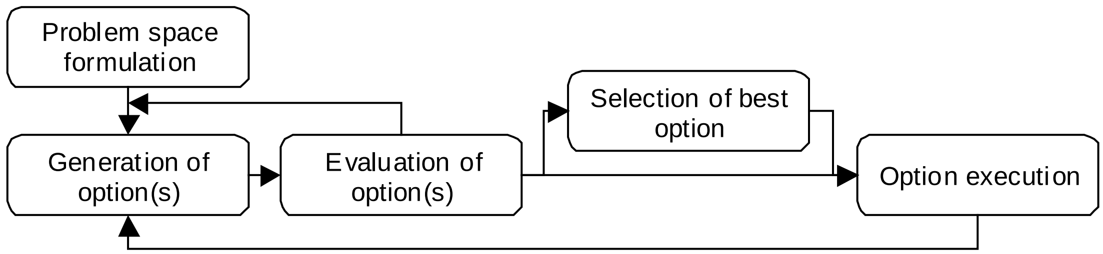


Figure 16 Problem-Space Search process.

representation, selecting an option (a solution or partial solution), "executing" the selected option, and monitoring the result of option execution.

Problem-Space Search

The Problem-Space Search model of problem-solving was developed by Newell and Simon [193, 250, 249], based on the assumption that a human is an information-processing system—at least when solving problems. It has been adopted in a variety of research, most notably efforts in artificial intelligence. (Note that, despite—or perhaps because of—its widespread acceptance, this model does not seem to have a common designation. "Problem Space Search" is a descriptive designation adopted in this dissertation.) Newell and Simon first develop a theory of an information-processing system (a set of processes and mechanisms) that could produce human problem-solving and decision-making behavior. They then use this theory to analyze behavior observed in laboratory settings in the domains of cryptarithmetic, symbolic logic and chess, and demonstrate that the theory can account for the observed behaviors. Finally, it combines the theory and the empirical evidence to propose a computational model that not only describes human problem-solving behavior, but also provides a generalized mechanism for simulating it.

Problem-Space Search describes problem-solving as "an interaction between an *information-processing system*, the problem solver, and a *task environment*, the latter representing the task as described by the experimenter" [249, p. 272]. The first step in the problem-solving process (Figure 16) is for the problem-solver to construct a *problem space*, which is "his way of viewing the task environment" [ibid.], that is, a mental representation of the problem. The problem space "represents the problem elements …, relations among problem elements …, and the initial and goal states of the problem" [249, p. 284]. It includes knowledge of acceptable solutions as well as a set of transforming rules that converts current knowledge into new knowledge. The problem space is modeled as a state transition graph, wherein each node represents a particular state of knowledge and arcs represent the application of transforming rules.

Actual problem-solving is then characterized as a search for a path that leads from the initial state to a state or states corresponding to the given goal state(s). Newell and Simon note that this formulation is theoretically equivalent to a set-theoretic characterization, in which the problem-solver is given a process for generating possible solutions and a means for testing whether a generated option is an acceptable solution. With this generate-and-test method, "the problem of finding a path [is replaced] with the problem of finding the final element of the path" [193, p. 98]. While they explore the theoretical equivalence of the two models thoroughly, they develop only the search representation and its application to analyzing observed behavior fully. The set representation, however, will be useful when comparing Problem-Space Search with Naturalistic Decision-Making.

At first, the problem space contains the initial and goal state(s), but may lack intermediate states on paths connecting the two. In the course of problem-solving, the problem-solver may thus need to expand the set of "known" states. New states are generated by selecting an appropriate transforming rule and applying it to an existing state, thus creating "new" knowledge and adding possible path options. Such transformation is a process of making information that is implicitly available in the system explicit, rather than adding new information: A key assumption of the Problem-Space Search model is that information must be contained—either implicitly or explicitly—in the problem space if it is to figure in the problem-solving process.

The Problem Space Search model provides for several ways of altering the course of the search. First, it provides for several possible means of selecting a transformation rule to apply, e.g., based solely on the end goal, based solely on the current state or based on a combination of the two. In many cases, only one rule needs to be considered and applied. This yields *singular evaluation*, in which the result of the transformation is evaluated based only on its own characteristics. In other cases, multiple rules may compete for application, and the problem-solver must evaluate which to apply or which result to pursue, i.e., select one of the rules over the others, or apply all of the rules and select one of the results over the others. This yields *comparative evaluation*, in which two or more options—either rules or knowledge states resulting from their application—are evaluated by direct comparison of their characteristics.

Note that comparative evaluation is consistent but not necessarily synonymous with a rational choice model. Newell and Simon and Simon's further efforts [249, 250, 252] emphasize that humans do not necessarily examine all possible choices in order to select the best, nor do they necessarily compare options on all possible characteristics. Rather they employ heuristic methods to guide the search and provide approximate evaluations.

If a path being examined does not appear to lead to a solution or ends without having led to one, the problem-solver may deliberately backtrack (revert to a previously encountered state) and restart the search from there by selecting a previously discarded option. The trial and error represented by such backtracking is considered inherent to the problem-solving process. The problem-solver may also reformulate the problem space entirely, either because of new information from the external environment or because of insights gained in the course of the search. Such problem space reformulation is considered extrinsic to the problem-solving process, in essence, restarting it.

The process outlined by the Problem-Space Search model is shown in Figure 16. The detailed model exhibits three characteristic features. First, all information used in solving the problem must, at some point, be included in the mental representation. Second, although the mental representation may be expanded in the course of problem-solving, a complete reformulation thereof is considered cataclysmic and is not inherent to the problem-solving process. Third, three possible ways of generating and evaluating options are possible: singular evaluation of both rule and its application, comparative evaluation of rules and singular evaluation of the application of the selected rule, or comparative evaluation of the applications of several rules.

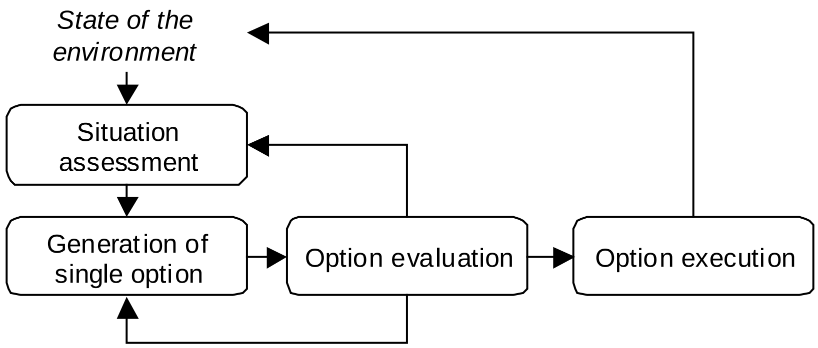


Figure 17 Naturalistic Decision-Making process.

It should be noted that the problem-solving processes illustrated in the empirical studies offered by Newell and Simon emphasize comparative evaluation, so the Problem space search model is often assumed to require comparative evaluation. However, the underlying computational model provides for singular evaluation and many of its subsequent applications have modeled problem-solving processes that exhibit primarily singular evaluation.

Naturalistic Decision-Making

The Naturalistic Decision-Making model arises from a community of researchers working on the assumption that the rational model is an inappropriate standard for human behavior and is not in accord with observations of expert behavior. The Naturalistic Decision-Making community studies decision-making by experts in real-life situations, such as military fighter pilots, battle commanders, fire fighters, emergency medical care personnel [147, 289], using ethnographic methods including gathering extensive observational and interviewing protocols[xxxi]. The Naturalistic Decision-Making model is receiving increasing attention and wider acceptance in efforts to model and train real-world decision-making.

[xxxi] Detailed verbatim transcripts of observed behaviors and utterances used extensively in social, behavioral and psychological research.

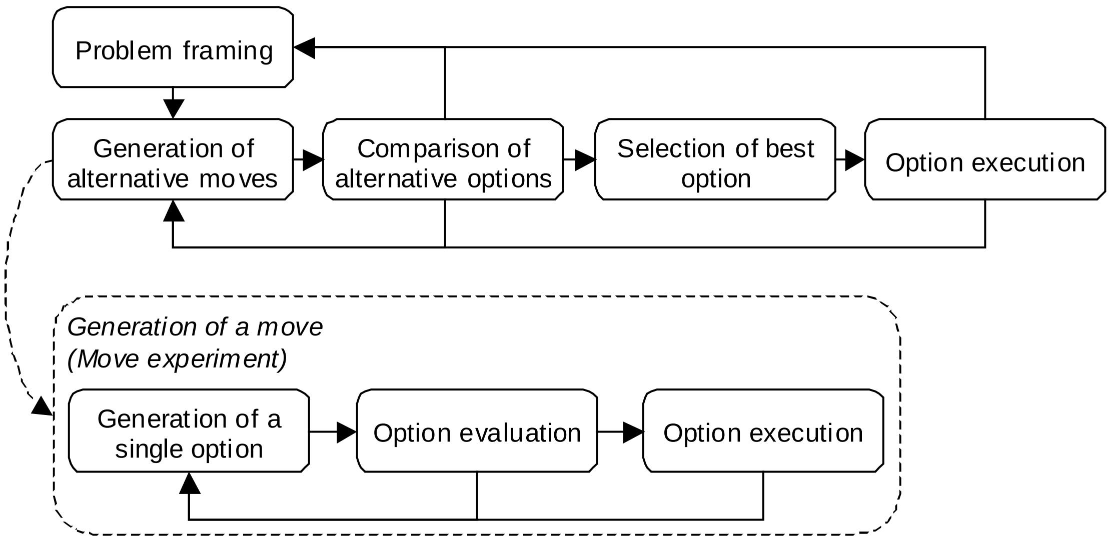
Most Naturalistic Decision-Making researchers focus on specific aspects of problem-solving and decision-making and do not offer explicit models of the overall process. However, they seem implicitly to agree on the general model outlined by Endsley [71][xxxii], shown in Figure 17. As in the Problem-Space Search model, the first step in the Naturalistic model is the development of a mental representation of the problem, in this case, *situation awareness*—"a person's state of knowledge about a dynamic environment" [71, p. 60]. Situation awareness comprises three levels of understanding. Level 1 is an understanding of "the status, attributes, and dynamics of relevant elements in the environment" [71, p. 36]. Level 2 is an understanding of "the significance of those [Level 1] elements in light of pertinent operator goals" [Ibid., p. 37]. Level 3 is a projection of "the future actions of the elements in the environment—at least in the near term" [Ibid.].

The decision-maker then uses this assessment to draw on their past experience to generate a possible option for the next step in addressing the problem. This option is then evaluated—often using mental simulation—to determine its viability, that is, to examine whether it will work and ensure that it has no "fatal flaws." If the option is found to have minor flaws, the problem-solver seeks to find ways of addressing them by repeating the general problem-solving process. When an option is deemed acceptable, possibly after the necessary revisions, it is executed. Thus, evaluation is not comparative and is intended to ensure that the option is acceptable rather than the best possible [34, 146, 170]. In general, a second option is generated and evaluated only after the first option is rejected.

Updating and revising situation awareness is an integral part of the decision-making process in this model. If the decision-maker is unable to generate an acceptable option, they may deliberately seek to revise their situation awareness. They frequently

---

[xxxii] While Klein has greater recognition as an authority on Naturalistic Decision-Making, he offers his model of recognition-primed decision-making [145, 146] as "an example of a Naturalistic Decision-Making model" [146, p. 287] rather than a model of Naturalistic Decision-Making. Endsley offers a less specific model, but presents it as a general model of Naturalistic Decision-Making.



The dotted arrow indicates expansion of the "move generation subtask" not control flow.

Figure 18 Reflective Problem-Solving process.

also revise or update their situation awareness after an option has been put into effect, in order to reflect changes in the external action resulting from such action. This is reflected in Figure 17 by a feedback loop between the external environment and the decision-maker that is mediated by the execution of decisions.

The Naturalistic Decision-Making model (Figure 17) thus exhibits three characteristic features. First, situation assessment (updating or revising situation awareness) is a continual and critical part of the process and accounts for a considerable portion of the decision-maker's effort. Second, progress is dependent on a feedback loop that provides the decision-maker with new information from the external environment. Third, options are evaluated singularly without comparison to other options.

Reflective Problem-Solving

The concept of Reflective Problem-Solving was developed by Schön [235] in response to the predominance of the model of *Technical Rationality* in professional training and education. According to Technical Rationality, "professional practice is a process of problem *solving* [that is independent of] problem *setting*, the process by which we define the decision to be made, the ends to be achieved, the means which may be chosen" [235, p. 39-40]. To counter this view, Schön presents a set of case studies of problem solving by professionals in a variety of planning and design professions—architecture, psychotherapy, industrial and electrical engineering, urban planning, and industrial management. The Reflective Problem-Solving model stems from Schön's observation of design practice and extensive personal experience with architectural design and is accepted within the limited community studying the cognition of design.

As in the other models, the first step in the Reflective Problem-Solving model (Figure 18) is the development of a mental representation. Schön calls this *problem framing* or *setting*—"the process by which we define the decision to be made, the ends to be achieved, the means which may be chosen" [235, p. 40]. This results in a *problem frame*—a conceptualization of the problem. The problem-solver then proceeds to conduct *move experiments* within that problem frame. A *move* is a change to a physical or imagined representation of a possible solution, and a sequence of moves results in a complete or partial solution to the problem as defined by a given problem frame. Progress is dependent on observed results from individual moves, resulting in a feedback loop like that exhibited by the Naturalistic Decision-Making model (cf. Figure 17 and Figure 18).

As in the Naturalistic Decision-Making model, individual move options are generated and evaluated sequentially, without comparison to other options. However, the problem-solver may conduct several different move experiments within a single problem frame, and as in the Problem-Space Search model, compare the resulting solutions to each other, selecting the best or most promising for continued development. They may even choose to develop multiple options simultaneously.

When move experiments fail severely or consistently, the problem-solver may "re-frame" the problem, discarding one problem frame and developing a new one. They may also deliberately experiment with different problem frames. As in move experimentation, during *frame experimentation*, options may be generated and evaluated either singularly or comparatively. Schön describes this type of problem-solving as "a reflective conversation with the situation" [235, passim] in which the problem-solver experiments with different ways of conceptualizing the problem and different ways of manipulating

	Problem-Space Search (Figure 16)	Naturalistic Decision- Making (Figure 17)	Reflective Problem-Solving (Figure 18)
Mental representation	Problem space	Situation awareness	Problem frame
Process	Sequential • Problem space formulation • Progressive search of problem space	Iterative • Situation (re)assessment • Decision-making • Decision-execution	Alternating • Problem (re)framing • Move experimentation
Distinguishing characteristics	• All necessary information (eventually) contained in mental representation • Revision of mental representation not integral • Singular or comparative evaluation of options	• Feedback from external environment essential • Mental representation updated/revised continually • Singular evaluation of options	• Alternation between problem framing and solution development • Necessary information may remain implicit in external problem setting • Feedback from representation of solution essential • Mental representation revised deliberately • Singular and comparative evaluation of options

Table 1 Characteristics of general models of problem-solving and decision-making

the situation within that conceptualization[xxxiii]. A key assumption in this model is that some of the information that figures in problem-solving may be implicit in the external problem setting and may not be encoded in the mental representation.

[xxxiii] The astute reader will have noted that this is, in essence, a different formulation of the canonical design process grossly outlined in Chapters 1 and 2. They will also have

The Reflective Problem-Solving model (Figure 18) thus exhibits five characteristic features. First, the process alternates between experimentation with different problem frames and experimentation with different solutions within a given frame. Second, some information used during problem-solving may remain implicit in the problem setting. Third, progress depends on feedback resulting from manipulation of physical or imagined solution representations. Fourth, problem frame manipulation is a fundamental and essential step of the process. Fifth, both frame and move experimentation may use either singular or comparative evaluation of options.

Comparing the Models

The key characteristics of each of the three models of general problem-solving and decision-making are summarized in Table 1. While there are distinct and obvious differences among them, they also have considerable commonalities.

Differences among the Models

The three models exhibit substantive differences along four dimensions. First, they differ in the role of the problem context in problem-solving and decision-making. In Problem-Space Search, the problem context is reduced to a mental abstraction and all necessary information must be encoded in the mental representation. In Naturalistic Decision-Making, the problem context changes dynamically, both independently and as a result of decision execution. It thus plays an independent role that cannot be abstracted mentally. The Naturalistic Decision-Making literature suggests that all necessary information is encoded in the mental representation, although the problem-solver may not be consciously aware of it. Reflective Problem-Solving lies between these two with the problem context playing a semi-independent role, yet being partially (and variously) abstracted. Some necessary information may not be encoded mentally, but may reside in the problem setting or emerge from manipulations thereof.

---

noted that frame experimentation corresponds to the imposition of different constraint sets, and move experimentation to imposition of individual constraints.

	Problem-Space Search	Naturalistic Decision- Making	Reflective Problem-Solving
Problem-solvers studied	Novices, Chess experts	Domain experts (acknowledged expert decision-makers)	Domain experts (professional practitioners)
Study setting	Laboratory	Field study and interviews	Field study and introspection
Problem context	Static	Highly dynamic	Malleable
Problems studied	• Short-term, moderately difficult symbolic (puzzle-like) problems • Low stakes • Attentional time bounds • No vested interest	• Planning problems resulting in course of action • High stakes • Time-critical • Professionally and personally vested interest (often personal safety)	• Planning problems resulting in artifacts or plans • Low stakes • Pragmatic time bounds • Professionally vested interest

Table 2 Contexts in which general models of problem-solving and decision-making were developed

These differences may result from the settings and types of problems that were studied in the course of developing the respective models (Table 2). The Problem-Space Search model reflects task-driven problems studied in self-paced situations, where the problem-solver is in complete control. The Naturalistic Decision-Making model reflects event-driven problems studied in situations that are controlled by external forces. The Reflective Problem-Solving model reflects task-driven problems, but the settings in which they were studied were partially controlled by external forces.

Second, the models differ in the role of the mental representation in problem-solving and decision-making. In Problem-Space Search, the problem space constitutes sufficient and necessary context for problem-solving. All information necessary to reaching a solution must be available in the problem space. In Naturalistic Decision-Making, situation awareness is used to elicit possible options from memory. In Reflective

Problem-Solving, the problem frame provides a framework for eliciting options from memory and a context for experimental manipulation of options. Information

These differences may reflect the types of problems studied and the level of experience of the problem-solvers studied. The Problem-Space Search model was developed from studies of self-contained puzzle-like problems solved by novices, and in the case of chess problems, by experts. The Naturalistic Decision-Making model is based on studies of situated problems solved by domain experts such as fireground and battle commanders. The Naturalistic Decision-Making model drew on studies of speculative problems tied to real-world situations and solved by expert practitioners such as architects and urban planners.

Third, the models differ in the nature of the overall process they portray. Problem-Space Search offers a sequential process (Figure 16), with development of the mental representation followed by a progressive search (which is iterative). Although the mental representation may be expanded during the search, it is not restructured fundamentally. Fundamental reconstruction is considered cataclysmic with respect to the immediate problem-solving process, although it is recognized as a component of a larger process.

The process portrayed by Naturalistic Decision-Making (Figure 17), in contrast, is iterative, with construction of the mental representation followed by decision-making and decision-execution, resulting in reassessment and possible total reconstruction of the mental representation. Reflective Problem-Solving (Figure 18) is again in the middle, with a process that alternates between reconstruction of the mental representation and iterative exploration of solutions. These differences, like the two previously described, may reflect differences in the nature of the problems studied and the situations in which they were solved.

Finally, the three models differ as to whether options are evaluated singularly or comparatively. Problem-Space Search offers the full range of possibilities (although, as mentioned, it is often interpreted as offering only comparative evaluation). Naturalistic Decision-Making maintains that singular evaluation is the norm. Reflective Problem-Solving represents a middle ground, holding that problem-solvers engage in a mix of singular and comparative evaluation. These differences may reflect differences in the expertise of the problem-solvers studied. Experts (as studied for the Naturalistic Decision-Making and Reflective Problem-Solving models) may have a richer set of transformation and selection rules (cf. *Problem-Space Search*, p. 97) that allow them to generate and select options without externalizable[xxxiv] evidence of doing so. Novices (as studied for the Problem-Space Search model), lacking such advanced rule sets, may perform more obvious experimentation.

The differences may also reflect differences in the time allotted for solving problems and the cost of failure. The studies underlying the Problem-Space Search model placed no time limits on problem solving, and there were no consequences for failure to solve problems. In the situations in which Naturalistic Decision-Making was studied, in contrast, time is often a critical factor (e.g., action must be taken before the house is burned to the ground or the patient dies) and the cost of failure high, potentially in both psychological (e.g., loss of life or material goods for others) and physical terms (e.g., loss of life or health of the problem-solver themselves). Reflective Problem-Solving represents the middle ground with problems imposing pragmatic time bounds, and consequences of failure potentially high in professional and psychological terms, but low in physical terms.

Note that the frame experimentation of the Reflective Problem-Solving model represents a slight difference among the models in whether defining the overall goals and objectives (agenda-setting) is considered part or beyond the scope of the problem-solving and decision-making process. The Problem-Space Search model implies that the goals and objectives are given in the task environment, although Simon, in later work, explicitly defines problem-solving to include agenda-setting [252]. The Naturalistic Decision-Making model, as exemplified by Endsley [71], explicitly assumes that the goals and objectives are defined outside the decision-making process. However, both the Problem-Space Search and the Naturalistic Decision-Making models recognize agenda-setting as a necessary precursor to problem-solving and decision-making. Thus, this distinction is more a semantic than a philosophical difference.

[xxxiv] I.e., observable by others or reportable by the problem-solvers themselves.

Commonalities among the Models

Despite these differences, there are four points of significant agreement among the models. First, while they differ in the details, all three outline a process comprising four basic steps (Figure 19):

1. Develop/update a mental representation of the problem and its context.
2. Generate and select an option for "action" that is expected to lead to a solution.
3. "Execute" the selected option.
4. Monitor or evaluate the result of option execution.

They also agree that while this process is progressive, that is, that progress is incremental, it may not always be cumulative. Apparent progress may be discarded and the process resume at what appears to be an earlier stage. This implies that all three models allow for trial and error.

Second, the models agree that the quality of the mental representation determines, in part, the ease and success of the problem-solving process. They also agree that the quality of the mental representation depends on how successful the problem-solver/decision-maker has been in recognizing and incorporating critical features of the problem and its context. While Endsley [71, 72] offers more detail on the contents of the mental representation, all three models agree that the critical features include relevant elements of the problem situation and relationships among them.

Third, the models agree that consideration of different options is integral to the process, although they differ in how options are generated and selected—resulting from the application of transformational rules or retrieved from memory, and evaluated singly or comparatively. Fourth, the models agree that some form of "executing" options—whether mentally or physically—is necessary to progress, and that this execution is monitored to verify that the option is executed correctly, and its results are as expected.

Competing Models or Alternate Strategies?

These three models of general human problem-solving and decision-making were, as stated earlier, developed at least in part in response to evidence that human behavior

	Comparative Evaluation (Problem Space Search strategy)	Combined Comparative and Singular evaluation (Reflective Problem-Solving strategy)	Singular Evaluation (Naturalistic Decision-Making strategy)
Time pressure	Low -- High		
Experience	Low -- High		
Context	Stable --Rapidly changing		
Goals	Well-defined ------------- Ill-defined ---------- Somewhat ill-defined		
Need for justification	High ---Low		
Conflict resolution	High ---Low		
Optimization	High ---Low		
Computational complexity	High ---Low		

Table 3 Conditions that drive problem-solving and decision-making strategy selection. (Adapted from Klein [146, p. 95].)

Entries suggest a spectrum of values and indicate the point at which a particular strategy is likely to be favored.

does not fully match the rational models offered by classical decision theory. Problem-Space Search bears the strongest resemblance to a rational choice model with its option of comparative evaluation that seeks to select the best or most promising of a set of options. Naturalistic Decision-Making, with the singular evaluation model that seeks the first acceptable solution, bears little resemblance. Reflective Problem-Solving, with elements of each of the others, bears some resemblance.

Despite their dissimilarities, however, all three models can be seen as describing differing strategies for compensating for human limitations in dealing with the complexity of the world. That all three agree with human problem-solving behavior in some context raises the possibility that they may model alternate strategies rather than offer competing models. That is, the behavior of a problem-solver might conform to one or the other model, depending on the type of problem they are given and the circumstances in which it is given. This supposition seems strengthened by the observations that the models differ primarily in their details and agree in the overall process. This is borne out by evidence that the computational mechanism of the Problem space model can simulate Naturalistic Decision-Making.

Klein, a pioneer in the study of Naturalistic Decision-Making, explicitly discusses alternate strategies: “There are times to use comparative strategies and times to use singular evaluation strategies” [146, p. 95]. He identifies eight conditions that influence the choice of strategy in a given situation (Table 3), including properties of the problem-solver, the problem and the circumstances under which the problem is to be solved. The only property of the problem-solver that affects strategy selection is the degree of their experience in the domain, with novices using comparative evaluation (as offered by Problem Space Search) and experts tending to singular evaluation (as offered by Naturalistic Decision-Making). Properties of the problem itself include how clearly the goals are defined, whether and how rapidly its context changes, and how complex the problem is computationally. The properties of the problem situation include how quickly a solution is needed, whether justification must be presented for the solution selected, whether the selection of a solution is controversial or must resolve conflicts, and whether an optimal solution is desired.

That the three models reflect different strategies and that strategy selection depends on properties of the problem-solver is intimated by Simon in later work: “The expert's 'intuition' and 'judgment' derive from this capability for rapid recognition linked to a large store of knowledge. When immediate intuition fails to yield a problem solution or when a prospective solution needs to be evaluated, the expert falls back on the slower process and analysis and inference” [250]. It is also notable that Naturalistic Decision-Making seems to resemble to the “generate-and-test” method of problem-solving that Newell and Simon [193] discuss as being theoretically equivalent to Problem-Space Search (cf. *Problem-Space Search,* p. 97). That is, if a set of solutions—such as an expert has in their memory—are presented along with the problem, the problem-solver theoretically has the option of resorting to “generate-and-test” rather than Problem-Space Search, according to Newell and Simon.

Regardless of whether the three models represent models of alternate strategies or are competing models, the first step in supporting any of them is to support their commonalities. This entails understanding what mental representation is necessary to solve the given type of problem—what the “critical elements” are and which relationships among them need to be understood. It also requires an understanding of what constitutes an "option," as well as what specific environmental factors affect the problem-solving and decision-making process and how they affect it. These basic components are independent of the problem-solving and decision-making strategy the user selects, while the best way of presenting them may not be. This dissertation is primarily concerned with whether and how the basic components can be identified from existing psychological knowledge, in the context of wayfinding problem-solving and decision-making, rather than with understanding how they should be presented to the user in different contexts.

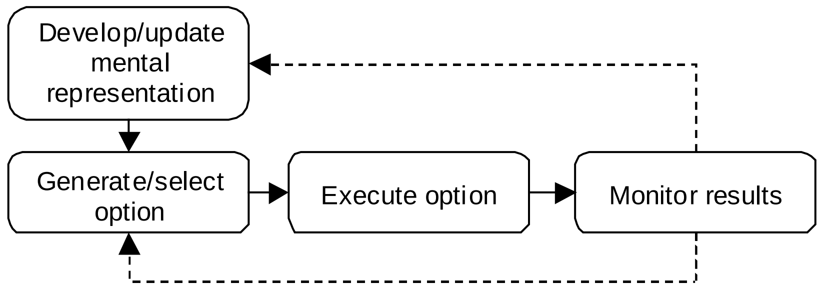
Wayfinding Problem-Solving and Decision-Making

Assuming that "A human being is confronted with a problem when he has accepted a task but does not know how to carry it out" [249, p. 272], wayfinding is clearly a matter of problem-solving. The supposition that humans apply general cognitive processes of problem-solving and decision-making to wayfinding problem-solving and decision-making has been argued explicitly [31, 67, 141, 174, 213, 245, 258, 268] and underlies much navigational research. However, it should be verified if a design theory of wayfinding derived from models of general problem-solving and decision-making is to be expected to produce the desired results. After all, it is possible that humans, in actuality, solve wayfinding problems in completely different ways from other types of problems. For example, they might employ purely physiological processes—like Superman's x-ray vision—that eliminate the need for cognitive processing altogether. Or they might rely on external mechanisms—such as divine inspiration or the collective consciousness of Star Trek's Borg[xxxv]—that delegate all or parts of the processing to other agencies.

Evidence that supports the assumption comes from two sources. First, direct observations of wayfinding behavior points to a cognitive process that is similar, if not

---

[xxxv] The Borg is a fictitious species of space aliens that, through advanced technology, depend on shared consciousness, so that what is known by one individual is known to all.



Dotted arrows indicate differences among the models.

Figure 19 Common problem-solving and decision-making process.

identical, to the general process of problem-solving and decision-making. Second, mathematical and computational models of human wayfinding that are based on problem-solving and decision-making theory, or particular elements thereof, successfully predict or simulate wayfinding behavior or performance, albeit in limited contexts. Finally, there is evidence that different strategies for wayfinding conform to the three models of problem-solving and decision-making described, that is, that wayfinding behaviors are consistent with behaviors resulting from the general models.

Direct Observation of Wayfinding Processes

As has been discussed (*General Problem-Solving and Decision-Making,* p. 95), problem-solving and decision-making is an iterative process (Figure 19) in which a mental representation of the problem is developed, different possible options for action are generated, one of which is selected and, subsequently, executed, resulting in progressive cumulative progress toward some desired goal. Any behavior, aimed at solving some particular problem, that exhibits such a process can, presumably, be said to be an example of problem-solving and decision-making and assumed to employ the cognitive processes of problem-solving and decision-making. Descriptions of observed wayfinding behaviors portray such a process.

Passini [211, 213] describes a process—based on direct observation of wayfinding behavior—that is identical in form and structure to the general problem-solving and decision-making process. He characterizes wayfinding as "being composed of three major cognitive processes: first, a process leading to *spatial information* comprising the various aspects of obtaining, accumulating and structuring information, second, a process leading to plans of actions in [the] form of *decision plans*, and third, a process leading to *spatial behavior*" [211, p. 26]. In other words, Passini describes wayfinding as a process of developing a mental representation of a spatial problem, generating and selecting among possible options for spatial action, and executing selected options in the form of spatial behavior. He then describes the development of decision plans as "a *continuous* process that can deal with unforeseen problems whenever they occur" [Ibid.], implying that this is an iterative cumulative process.

Burns [31] combines Passini's description with the model of human information-processing presented by Wickens [280] to develop a model of wayfinding while driving in the physical world that bears a striking resemblance to the Naturalistic Decision-Making model presented by Endsley [71]—even to using the term "situation assessment" for developing a mental representation of the problem[xxxvi]. The Burns model of wayfinding presents an iterative process containing four steps: "Perception" (of either environmental information or retrieval from memory), "Situation assessment," "Decision" and "Execution." Endsley's model of problem-solving and decision-making presents an iterative process with the three steps: "Situation assessment" (in which the first step is "Perception of elements in current situation"), "Decision" and "Performance of actions."

Observational and experiential studies of non-technological systems of wayfinding reveal processes that resemble that offered by Naturalistic Decision-Making. For instance, systems used by Caroline Islanders [92] and Vikings [266] for cross-oceanic voyages both rely on expert knowledge of routes and their associated environmental cues, such as star positions, seamarks (e.g., reefs and wave systems) and observations of the solar ephemeris function[xxxvii]. Studies of the use of these systems detail journeys as continual cycles of assessing current travel conditions (wind, tides, weather, etc.),

---

[xxxvi] Although it is possible that Burns borrowed from the Naturalistic Decision-Making literature, he provides no evidence of this.

[xxxvii] The path of the sun across the sky on a given day at a given latitude.

recalling possible routes, selecting one and taking the necessary actions to follow that route [92, 158, 266]. That these systems should represent a Naturalistic Decision-Making process is consistent with their association with considerable expertise.

In use of technology-based wayfinding, Hutchins [124], describing wayfinding operations and procedures of the US navy, details a system for generating and evaluating wayfinding options. This system is codified in manuals and standard operating procedures and is consistent with Problem-Space Search. Distributed across several individuals, the process comprises four steps. First, environmental information is collected, e.g., by visual bearings, radar, Fathometer, satellite, etc. This information is then combined with navigational charts to calculate route options. Selection of an option depends on a variety of factors including characteristics of the ship (e.g., turning radius), standard policies (e.g., traffic lanes) and environmental conditions such as wind and tides. Execution of the selected option then depends heavily on the continued collection of environmental information.

A variety of studies suggest that consideration of different options is a critical component of wayfinding, and that different wayfinding circumstances may result in different options being selected. Gärling [86] reviews a variety of studies examining how attributes of the problem situation including spatial distance, importance of visiting a particular location and anticipated waiting time at a particular location affect route selection by experimental subjects. Elliott and Lesk [68] report that wayfinders seemed to optimize route selection for fewer simpler decisions (i.e., fewer decisions resulting in direction changes) rather than shorter distance. Streeter and Vitello [261] report similar results, but found that this tradeoff varied with subjects' familiarity with the study environment and their wayfinding ability. They also found qualitative differences in routes selected by novices and experts. These results are consistent with general problem-solving and decision-making processes.

Mathematical and Computational Models of Wayfinding

Evidence to support the view that wayfinding cognition employs general problem-solving and decision-making processes may also be found in mathematical and computational models. These models are derived from theories of problem-solving and decision-making and yield models of wayfinding behaviors or performance that are consistent with empirical data of actual behavior or performance. Best [25] and Dada and Wirasinghe [57] found that the number of wayfinders[xxxviii] becoming lost along a given route was highly correlated with the number of locations along the route at which a decision had to be made and the number of options offered at those points.

O'Neill similarly found that the number of decisions to be made and the number of options available was a good predictor for the number of errors wayfinders made [203, 204]. He used this and other evidence to build a computational model of spatial knowledge preservation and wayfinding (based on neural networks and spreading activation[xxxix]) that successfully matched human behavior in selecting routes through a simple environment [202, 205]. The wayfinding module of this program employs a process that is similar, if not identical, to that of Naturalistic Decision-Making—retrieving route options from "memory" and evaluating them without comparison to others.

Gopal and Smith [99] also developed a computational model of wayfinding behavior using spreading activation. This model exhibited the same types of errors in the course of route selection as those committed by human wayfinders.

It should be noted that these efforts to model wayfinding behavior and performance are closely related to efforts to model spatial knowledge. However, behavioral models differ in that they seek to predict actual behavior or performance, whereas knowledge models seek to provide examples of knowledge structures and acquisition processes that might account for spatial behaviors. Perhaps the most well-known example of spatial knowledge modeling is the work of Kuipers [153, 154, 155, 156] who describes how perceptual input might be transformed into a high-level cognitive map. Although he

---

[xxxviii] Both studies incorporate subjects who were familiar with the study environment as well as subjects who were not.

[xxxix] Spreading activation is a graph search technique in which search proceeds by selecting the most promising of a node's neighbors to search next. This technique contrasts with algorithms incorporating predefined search patterns, such as depth- and breadth-first search.

demonstrates the use of this knowledge in robotic wayfinding [156], the resulting behaviors are not compared to observed human behaviors. Therefore, in the remainder of this dissertation, Kuipers' work and similar efforts are cited only when it provides evidence for actual human cognitive processes.

Different Problem-Solving and Decision-Making Strategies in Wayfinding

Introspection, for most people, will likely bring up examples that employ both comparative and singular evaluation during wayfinding. Who, for instance, when driving to a new or little visited location in a familiar environment has not been asked, "Why are you going this way?" only to respond, "I don't know, I didn't think about it"? (That is, found themselves employing a strategy that conforms to Naturalistic Decision-Making.) On the other hand, who, in planning a vacation, for instance, has not pored over a map comparing possible places to visit, routings and itineraries? (That is, found themselves employing a comparative evaluation strategy.) Empirical evidence suggests that people employ both types of strategies during wayfinding, and that strategy selection depends on, at least some of, the conditions outlined in Table 3.

Gärling [86], when describing how attributes of the problem situation affect spatial decision-making, cites evidence for both Problem-Space Search and Naturalistic Problem-Solving strategies in travel planning in experimental settings. In the studies cited, strategy selection varied with computational cost of decision-making, with the Naturalistic Decision-Making strategy being favored when few destinations or attributes were presented, and the Problem-Space Search strategy being favored when many were presented.

Wright, Hull and Lickorish [285] found evidence for different planning strategies depending on the information available for wayfinding in a hospital setting, with some subjects planning their entire route before starting and others planning en route[xl]. While the former indicates a Problem-Space Search strategy, there is no evidence for what strategy or strategies were employed during the latter. These findings are consistent with

[xl] All subjects were initially unfamiliar with the study environment.

predictions based on wayfinding as a problem-solving and decision-making process involving different possible strategies.

Relationships between Wayfinding and Environmental Locomotional Design

The previous section showed that wayfinding might reasonably be assumed to be a process of problem-solving and decision-making and that the common process of problem-solving and decision-making shown in Figure 19 can be taken to represent wayfinding. In order to complete the understanding of wayfinding as a cognitive task, it is necessary to associate the general model with specific wayfinding behaviors, describing, for example, what mental representation is necessary to wayfinding and what is involved in developing one. Evidence for these behaviors may be found in the psychological literature, alongside evidence for how they are affected by environmental features. Thus, the completion of the first step in the design knowledge development process (understanding the cognitive task) is intertwined with the second step (understanding the relationships between the cognitive task and environmental locomotional design).

The analysis is guided by the four steps of the common process of problem-solving and decision-making. It first seeks to expose what elements of environmental locomotional design must be represented mentally in order to solve wayfinding problems. Although the present focus is knowledge necessary to solving wayfinding problems rather than on spatial knowledge preservation, this discussion draws heavily on evidence for the structure of cognitive maps and other forms of preserved spatial knowledge. This reflects an assumption that one of the primary purposes for storing spatial knowledge is to aid in future wayfinding problem-solving and decision-making [51, 64, 140, 152, 182, 245, 256, 265], and that, therefore, the stored knowledge must provide some indication of the type of knowledge necessary to wayfinding.

The analysis then seeks to determine what constitutes "options" in wayfinding problem-solving and decision-making, and what aspects of environmental locomotional design affect option generation and selection. The psychological literature does not dissociate option generation and option selection—for the most part measuring performance on the combined task—so these subtasks are discussed simultaneously.

Finally, the examination seeks to understand what properties of environmental locomotional design affect option execution. The literature is somewhat lacking in this area, because the focus of most research is on the physical relationships between steering design and locomotion, rather than on the cognitive aspects of completing the wayfinding task.

The analysis shows that the four problem-solving and decision-making subtasks each have clear implications in the wayfinding context. Developing a mental representation requires *path-identification*—identification of paths and locations available to the wayfinder in the environment. Generating wayfinding options requires *route-prediction*—predicting which of the available paths lead to the desired destination or meets other wayfinding goals. Selecting among these entails *route-selection*. Executing a wayfinding option is *route-following*—monitoring the actions and their results necessary to moving along a chosen route.

The analysis also reveals four categories of environmental locomotional design features that affect wayfinding performance. The first category is composed of factors that determine the characteristics of the *locomotional structure*—the set of locations and paths that are available to the navigator. The second category is composed of factors defined by the relationship between the superordinate task and the locomotional structure. The third category contains factors concerning relationships between the locomotional structure and other environmental structures such as perceptual and informational structures. The fourth category is composed of factors regarding the relationship between movement and locomotional structure.

Mental Representation

The goal of this part of the analysis is to identify the features of environmental locomotional design that must be represented mentally in order to solve wayfinding problems. Cognitive maps represent the sum of the spatial knowledge that can result from spatial behavior. This differs from the need of this dissertation, which is to identify what spatial knowledge is sufficient and necessary to wayfinding. Nonetheless, the cognitive mapping literature provides extensive information about what knowledge is necessary, as does the literature on other types of spatial knowledge (e.g., route knowledge) along with literature on representations of wayfinding solutions (i.e., route descriptions).

The development of a mental representation depends on information gathered from the environment, in other words, on the information-gathering subtask of navigation and the informational subdomain of navigational design. However, its necessary content depends on the wayfinding subtask and the environmental locomotional design subdomain. It is important to distinguish between features that affect the process of developing the representation and features that dictate its necessary content, and to separate features that provide information about the environmental locomotional design from features of the environmental locomotional design itself. Features that affect the development of the mental representation or that contribute information only, while necessary to a complete understanding navigation as a problem in design, are not the focus of the immediate problem of understanding wayfinding as a problem in environmental locomotional design.

The following analysis of what spatial knowledge is sufficient and necessary to wayfinding follows the three levels laid out by Endsley [71, 72] in her work on situation awareness in the context of Naturalistic Decision-Making (cf. *Naturalistic Decision-Making*, p. 99). Endsley's characterization of the mental representations necessary to problem-solving and decision-making is consistent with the characterizations presented by Simon [249] (cf. *Problem-Space Search*, p. 97) and Schön [235] (cf. *Reflective Problem-Solving*, p. 102), but offers considerable more specificity. The three levels, in summary, are an understanding of the relevant elements of the problem situation (Level 1), an interpretation of the significance of those elements in terms of the problem-solving goals (Level 2), and a projection of likely changes to those elements that might affect problem-solving (Level 3).

Level 1 Situation Awareness

Level 1 situation awareness comprises an understanding of the relevant elements of the problem situation. In the context of wayfinding, this must be in the form of spatial knowledge. Psychologists commonly recognize three types of spatial knowledge of a specific environment [107, 182, 245]: landmark, route and survey knowledge. The distinctions among these are particularly well described by McDonald and Pellegrino:

> Landmark knowledge is essentially familiarization with a location, a landmark, without knowledge of that landmark's position relative to other locations, nor of how to traverse between other locations and the landmark. Route knowledge is the knowledge of how to go from one location to another, but without definitive knowledge of the relative positions of locations. Most comprehensive of the three is configurational or survey knowledge, that is, a cognitive map, which is knowledge of the relative locations of objects in the environment [182, p. 51].

The structure and other properties of each of these representations and the roles of their various component elements have been the subject of extensive psychological research. The examination conducted here of the resulting findings reveals that the elements of environmental locomotional design that are represented mentally or affect the mental representation are locations, paths and two types of *decision points*—locations at which a wayfinding decision can or must be made.

Environmental Elements in Mental Representations

Lynch [172], in his seminal work on the structure of people's conceptions of urban environments, identified five distinct elements: landmarks, nodes, districts, paths, and edges. While these all represent environmental phenomena, some are significant because of their role in organizing the mental representation and structuring spatial behavior, while others derive their significance from the environmental phenomena themselves. Environmental phenomena that are significant because of their role in organizing the mental represent pertain more to the nature of that representation that to the information it represents. They are, thus, of limited interest in the present context. The examination, conducted here, of each of the five elements reveals that landmarks and districts are organizing features, while nodes are a specialization of the fundamental concept of location. Paths are clearly elements of environmental locomotional design. Edges, however, seem to be ambiguous and psychological knowledge about them is lacking.

Landmarks

Landmarks are the most familiar and—judging by the amount that has been written about them—the most popular of Lynch's five elements. A popular definition of "landmark" is "a prominent identifying feature of a landscape" [6]. However, in the psychological literature it is more commonly defined as a spatial reference point [51, 107, 119, 120, 140, 222, 232, 245], i.e., as a means of referencing spatial locations.

Landmarks primarily serve as organizing features [107, 119, 120, 140, 222, 232, 245], serving as *anchor points*—points that are used in defining the locations of adjacent points [55, 232]. Landmarks establish frames of reference around which people construct cognitive maps [55, 75, 118, 119, 222, 232, 245] and structure route knowledge [73, 222, 245, 261]. During wayfinding, landmarks may be used to help to maintain directional orientation during movement [109, 222, 245], e.g., by acting as beacons toward or away from which movement is directed [245, 277]. Landmarks also serve as "registration" markers—points of correspondence—between different representations of an environment or between a representation and the actual environment [222, 245].

Landmarks have been described as "unique configurations of perceptual events (patterns)" [245, p. 23], suggesting that they are part of the informational design rather than the locomotional design of the environment, that is, they affect what is known about where to go rather than changing where it is possible to go. Their role in organizing knowledge and in guiding rather than defining movement confirms this suggestion. That landmarks are part of informational design is further substantiated by evidence that any object or environmental feature is a potential landmark, but only becomes a landmark by virtue of its use as a spatial referent [51]. Classification of landmarks as informational design is also confirmed by evidence that wayfinders compensate for the absence or presence of specific types of prominent features by selecting others, without altering their locomotional choices or mental representations of locomotional options [51, 73, 109].

<u>Nodes</u>

Nodes are “the strategic foci into which the observer can enter” [172, p. 72], that is, they are places of special interest to the wayfinder. Nodes are typically associated with “concentrations”—locations of intense personal or public use, or of strong thematic unity, for example, a shopping center or a village square. They may also be associated with important path junctions, such as key or prominent intersections or transportation nexus.

Nodes define distinct spatial locations that serve as focal points in the organization of spatial knowledge, creating centers around which other elements are organized [119, 120, 172]. They also serve as defining points on paths. Without nodes—interesting places—paths risk becoming endless loops connecting nothing to nothing. Note that while nodes are locations to which a wayfinder moves, landmarks are locations relative to which a wayfinder moves.

Although nodes are an interpretation of a variety of possible environmental features, they represent an example of the more general concept of *location*. Because Lynch was studying “mental images” of spatial environments rather than detailed spatial knowledge, this more generic concept does not emerge. However, most studies of route knowledge and cognitive maps assert that locational information is fundamental [51, 64, 140, 213, 245]. Locational information has two components: a “what” or identifying component, and a “where” or positioning component [51, 64, 213, 245]. The “whereness” component—defining distinct spatial positions—is fundamental to wayfinding and environmental locomotional design.

In discussing nodes, Lynch describes path intersections as a frequent defining feature, but treats them almost incidentally: “In theory, even ordinary street intersections are nodes, but generally they are not of sufficient prominence to be imaged as more than incidental crossing of paths.” [172, p. 75]. Other literature on spatial knowledge and the features that affect wayfinding belie this cavalier treatment, and elevate intersections to much greater status. This literature will be discussed later (*Branch Points*, p. 127).

Districts

Districts are spatial regions that exhibit homogeneity along some dimension or dimensions [51, 120, 172]. For example, a forest or a cornfield is marked by a concentration of a certain type of plant and a college campus is often identifiable by architectural characteristics. The defining characteristics and boundaries of a district may be a matter of semantics rather than perception [120], for instance, geopolitical divisions between countries or states may not be readily apparent. Unlike nodes, which have a single defining element, districts are composites of multiple elements. Districts establish spatial regions by defining boundaries, in contrast to nodes, which may establish spatial regions by defining regional centers. Although districts, like nodes and landmarks, may serve as spatial referents in their containing environments [51, 172], they are often sufficiently large that they may, in themselves, constitute environments that can be navigated [119, 172, 259].

Districts introduce hierarchical structure into the organization of both cognitive maps [51, 119, 259] and route knowledge [213]. This permits wayfinding problems to be decomposed into sequential subproblems of inter- and intra-district wayfinding [68, 259, 260]. Although this potential for decomposing wayfinding problems may suggest hierarchical structure in locomotional design, districts result from the distribution of environmental properties made perceptible by the informational design. Like landmarks, they do not, in themselves, affect the locomotional opportunities offered by the environment.

Paths

Paths are “channels along which the observer customarily, occasionally, or potentially moves” [172, p. 47]. In other words, they are avenues of locomotion and, by definition, elements of the environmental locomotional design. Paths are fundamental elements in route knowledge [51, 107, 182, 245] and are the subject of route descriptions, in which they are specified in terms of behavioral actions that, typically, are indexed by elements of informational design [75, 148, 261].

Knowledge of paths is one of the distinguishing characteristics between landmark and route knowledge, as described above. It is, however, not inherent in the concept of survey knowledge [107]—knowing the spatial relationships between two locations does not necessarily imply knowledge of a path between them—and does not figure in theories of the properties of cognitive maps and in their ontogenetic development [107, 182, 245]. This absence notwithstanding, explanatory theories of the acquisition of cognitive maps suggest that paths are, in practice, fundamental to most cognitive maps [51, 98, 107, 245]. This is reflected in a division of studies of cognitive maps into those that focus on configurational understanding [120, 259, 267, 270] and those that focus on knowledge of paths [84, 98, 187, 205].

While paths are fundamental elements of the environmental locomotional design, it must be noted that a particular path is always defined with respect to a particular locomotional mechanism; what constitutes a path to someone in a car is considerably different from what constitutes a path to someone in an airplane. Rand [226] demonstrated that the mode of locomotion (the locomotional mechanism used) not only affects what options are available to the wayfinder, but also affects their conception of the environment. In studying the cognitive maps different individuals held of the same geographic area, he found consistent qualitative differences between the cognitive maps of pilots and those of taxi drivers, including differences in the specific elements—landmarks, paths, etc.—represented.

Edges

Edges are "the linear elements not used or considered as paths by the observer" [172, p. 47]. They are particularly interesting, if for no other reason than that they have received little, if any, attention since their identification by Lynch. Edges seem to be associated with two distinct environmental phenomena. First, they represent the boundaries between two "phases," such as between land and water, or between urban park and residential street. Second, they represent seams dividing otherwise unified areas, such as a row of trees cutting through a meadow, a freeway through a city, or even a line painted on a grassy field.

Lynch describes edges as both disruptive and unifying of spatial knowledge. When they are disruptive, the mental representation is partitioned and elements may be segregated and, possibly, isolated by their presence. For instance, the Golden Gate inlet to the San Francisco Bay isolates San Francisco to the south from Marin to the north. When they are unifying, they serve to organize other elements and are, in effect linear landmarks. A mountain range, for instance, may connect the elements on either side.

In addition to structuring spatial knowledge, edges may also figure in locomotion. Again, they seem to serve antithetical roles. On the one hand, they may actually be paths serving a different locomotional mechanism from that of the observer, e.g., a river viewed by someone walking, or railroad tracks by someone driving. Edge-paths may also serve the same locomotional mechanism, but represent paths that are part of a segregated system of paths, such as a system of limited access freeways intersecting local streets. On the other hand, edges may be systematic obstructions to locomotion, forming what might be termed "anti-paths." For instance, the trees might obstruct passage across the meadow and the freeway might obstruct passage across town.

In their role as organizing elements, edges are part of the informational design. As paths, they are, of course, elements of environmental locomotional design. Their role as "anti-paths," however, seems to imply that they may also represent a different kind element of environmental locomotional design. However, edges, in general, and this role, in particular, are insufficiently understood and too poorly documented, at this time, to be considered here. Any attempt to derive design implications from existing information would be purely speculative, and, while interesting, would not serve the purpose of understanding a means of extracting design knowledge from psychological knowledge. Consideration of edges is thus left until further psychological knowledge is available.

Environmental Elements that Affect Mental Representations

While Lynch's work was seminal in describing the elements of cognitive maps, other research reveals additional elements that are contained explicitly in mental representations or represented implicitly by the structure of mental representations. Lynch mentions path junctions, such as road intersections, as potential foci—the defining element—of nodes. Other efforts to study wayfinding cognition and its associated mental representations recognize the pivotal role of *decision* or *choice points*—locations where decisions may be made.

Careful examination of this literature distinguishes between two types of decision points. *Branch points* are locations, such as street intersections, where the available locomotional options change and a decision is executed (and therefore must be made). *Information access points* are locations where new information becomes perceptually available and a decision can be made (but not necessarily executed), for example, where a freeway crests a hill and offers a view of upcoming exits. Branch and information access points may coincide, for example, at doorways where locomotional options change and new information becomes available simultaneously. Locations that are both branch and information access points have been called *gateways* [51].

Branch Points

The significance of branch points is evidenced by their role in segmenting both spatial knowledge and spatial behavior. Chown et al. [51] offer an explanatory model of the development of cognitive maps based on environmental experience. They postulate a model of a cognitive map based on associative networks of "local maps"—representations of the view from a particular location when looking in a particular direction. They assert, "Because local maps code visual information, it is the act of stopping and looking around that is central to where they are constructed. … Therefore, one place that local maps will be created will be at [branch points][xli], such as at a fork in the road or a doorway" [51, p. 23]. Their model of the resulting stored spatial knowledge consequently yields segmentation at branch points.

Route knowledge is similarly segmented at branch points, with behavioral actions associated with branch points at which special action must be taken [84, 98, 217]. For instance, Gale et al. [84], studying the acquisition of specific route knowledge, found that "During route learning, more information is coded at intersections where choices are made than between intersections" [84, p. 19]. They showed that subjects who were able

---

[xli] Chown et al. use the term "choice point" for what is here termed "branch points." The terms "decision point" and "choice point" are used interchangeably and variously in the psychological literature to mean branch point, information access point or both. The more specific terminology was introduced here to avoid the ambiguity of these non-standardized usages.

to follow a route accurately were significantly better at identifying (as being on the route) images of views that were associated with intersections than those that were not. In fact, subjects recognized less than half of the latter.

Spatial behavior is also segmented at branch points, and all of the mathematical and computational models of wayfinding performance or behavior described earlier (see *Mathematical and Computational Models of Wayfinding*, p. 115) include a factor representing the number of branch points [25, 57, 174]. Observational studies similarly indicate that behavioral changes occur more frequently at branch points than at other locations [109, 181, 217].

Branch points are, unquestionably, a feature of the locomotional design. They represent locations where paths connect, making it possible to switch from one to another.

Information Access Points

Chown et al. point out that “Another place in which people are likely to pause and look around is when new information comes into view” [51, p. 23]. They assert that new information coming into view causes cognitive maps to be segmented at information access points in the same manner as they are at branch points. McCormick [181] found that wayfinding difficulty decreases with the presence of *vistas*—information access points that offer direct views of environmental topography: “53.4% of participants showed wayfinding difficulty when vistas and landmarks were absent, 48% when vistas were present, 38.5% when landmarks were present, and only 30.5% of participants showed wayfinding difficulty when both vistas and landmarks were present” [181, p. iii].

It is important to note that, unlike branch points, information access points do not seem to appear as basic elements in mental representations, they merely affect their structure, e.g., causing segmentation, as suggested by Chown et al [51]. If specific information access points are represented, they are associated with a node or landmark. That is, the information access point location does not have an explicit representation, but the *information point*—the location at which the information actually resides—does.

Information access points might seem to be features of informational design. However, while informational design may determine *what* information is available at an information access point, *where* the information access point is located depends on the relationships between the informational structure (dictating where the information points are), the pertinent perceptual structure (dictating the geometry of perception, e.g., lines of sight) and the locomotional design. For example, a vista point at the top of a hill is only an information access point if the path goes over the hill (rather than around) and if there is no fog to obscure the view. Thus, while information access points are not a property of locomotional design, locomotional structure plays a key role in their placement.

Although not described in any of the efforts cited, there is an implicit relationship between information access points and branch points that is particularly relevant to design. An information access point provides information about locomotional options, that is, about the choices that are available at one or more branch points. Thus, an information access point and a branch point are here defined to be *associated* if the information access point provides information relevant to a decision that can be executed at the branch point. An information access point that is not associated with any branch points is defined to be a *false information access point,* and the non-existent branch point(s) about which it seems to provide information is defined to be a *phantom branch point*. These distinctions are particularly important in a design context, but will also be useful in the continued analysis of the psychological evidence.

Critical Elements of Environmental Locomotional Design

The preceding analysis of the psychological literature found that two elements of environmental locomotional design are necessary to Level 1 situation awareness during wayfinding. These are shown, primarily by Lynch's work, to be locations and paths. The relationships between them that must be understood for Level 1 situation awareness are the ways in which the locations and paths are associated—which paths connect which locations—and the ways in which paths intersect—the branch points. The analysis determined that information access points are an environmental feature that results, in part, from environmental locomotional design, but which is not represented mentally.

The term *locomotional structure* is introduced here to denote a structure of interconnected locations and paths, as these are not only important to cognition, but, as shall be seen, a key element of locomotional design. A few observations about locomotional structures will aid further analysis of their role in wayfinding cognition. First, a locomotional structure must be defined with respect to a particular locomotional mechanism or combination of mechanisms. Second, an environment may offer multiple locomotional structures that may or may not be interconnected. If they are connected, they can be considered a single structure composed of multiple substructures. Third, while information access points are an attribute of a locomotional structure, they are not a defining element of locomotional structure.

Gaining Level 1 situation awareness implies developing a mental representation of relevant portions of the locomotional structure offered by the locomotional design (considering both prosthetic and environmental designs). The term *perceived locomotional structure* is introduced here to denote a locomotional structure that is encoded in a mental representation, in order to distinguish it from the *actual locomotional structure*—the structure that is offered by the locomotional design.

The perceived locomotional structure represents knowledge at the "spatial level of information" in a classification of spatial knowledge developed by Teske and Balser [265]. Note that the perceived locomotional structure may change in the course of wayfinding and may not encompass the entire actual locomotional structure at any given time. It is sufficient that, at any branch point, the current perception allows sufficient understanding to make a decision. Note also that the perceived locomotional structure need not reflect the actual locomotional structure accurately. It must only bear sufficient resemblance that the wayfinder is led to making correct decisions.

The process of developing Level 1 situation awareness—understanding of "the status, attributes, and dynamics of relevant elements in the environment"—during wayfinding is here termed *path-identification*. Path-identification is predominantly a perceptual task [181] that requires the wayfinder to recognize that an observed environmental feature is an instance of "location" or "path" [217]. This is more properly considered a subtask of information-gathering than of actual wayfinding.

The factors that affect path-identification are, consequently, matters of perceptual and informational design. That is, if the wayfinder is to develop an understanding of the locomotional structure preparatory to making a decision, they must have perceptual information that indicates when branch points have been reached and where some of the paths available from that point begin. Additionally, they must know, if such information is not available perceptually, what actions to take to select one of the paths. In other words, what locations and paths are available is locomotional design, while the information necessary to detect their presence is informational design.

As path-identification is more closely related to information-gathering and the factors that affect it predominantly informational design, it will not be considered in further detail. Most notably, wayfinding errors that are due to misperceptions—resulting in discrepancies between perceived and actual locomotional structures—will not be considered. Thus, the remainder of this dissertation assumes that the wayfinder's perceived locomotional structure is a correct, albeit possibly partial, approximation of the actual locomotional structure.

Level 2 Situation Awareness

Level 2 situation awareness implies interpreting the elements identified at Level 1 in terms of the "pertinent operator goals" (cf. *Level 1 Situation Awareness*, p. 120). Wayfinding is here presumed to be spatial problem-solving and decision-making undertaken to meet the needs of some superordinate task. That is, the wayfinding task is invoked because the superordinate task requires the wayfinder to go to some particular location or to traverse a certain path in the course of its performance. Operator goals are thus determined by this superordinate task. It determines *which* locations or paths must be visited or traversed, and sets the wayfinding agenda. Determining *where* those locations and paths are in the environment and *how* they can be reached is part of the wayfinding task. As the poet said, "if you don't know where you're going, any road will get you there," that is, if no goal is defined, wayfinding is unnecessary.

Locations that are the goals of wayfinding activity are here termed *destinations* or *target locations.* Paths that are the goals of wayfinding activity or that lead to destinations are called *routes* or *target paths.* Note that, under the definition of problem-solving and decision-making used here where agenda-setting is part of the superordinate task[xlii], for wayfinding to have meaning at least one destination or route must be selected, at least temporarily, as the ultimate goal. Teske and Balser [265] call this the “functional level of information,” using the terms “destination” and “itinerary” for destination and route, respectively.[xliii] McCormick [181], likewise, differentiates between the locations and paths offered by the environment and the destinations and routes defined by the task. She uses the path/route terminology, but does not offer explicit terminology for location/destination.

Most psychological studies differentiate between elements that exist in the environment and the conceptual elements used to represent them in the mind. However, other than those already cited, none explicitly differentiate between general spatial knowledge and goal-directed (or task-dependent) knowledge. Thus, for example, the acquisition of “route” knowledge is often studied by requiring subjects to learn to recognize and follow a specific path through the environment absent a goal or task other than learning the path. Conversely, much research on cognitive maps, ostensibly studying spatial knowledge, actually focuses on cumulative functional knowledge (i.e., reflecting a variety of goals and tasks) and does not ask subjects to report all spatial knowledge.

Understanding the distinction and relationships between the two types of knowledge, is, however, critical to design aimed at minimizing the effort required to perform a task. Such design must require only sufficient and necessary knowledge from the user, ensuring that the user is only required to acquire useful information. This is particularly important in the design of electronic environments where it is possible to

---

[xlii] Note also that this division follows the more restrictive definition of “problem-solving and decision-making” employed by both the Problem-Space Search and Naturalistic Decision-Making models of general problem-solving and decision-making.

[xliii] Their research was aimed at understanding the effect of environmental experience on the ability to identify information at the spatial and functional levels, and does not contribute to the present work beyond offering this distinction between spatial and functional information.

manipulate the elements that exist in the environment to accommodate the conceptual elements needed to represent them.

The development of Level 2 situation awareness entails mapping the destinations and routes dictated by the needs of the superordinate task to the locations and paths identified in Level 1 situation awareness. This process involves spatial reasoning about which paths might lead to which locations and, possibly, reasoning about which of these locations might be the desired target. The term *route-prediction* is introduced here to denote the process of predicting which locations might be destinations, and which paths might represent routes to the desired destination. Predicting routes constitutes the generation of possible solutions or partial solutions. That is, route prediction actually represents the option generation step of problem-solving. The properties of the environment, specifically of the locomotional structure, that affect route prediction will, consequently, be discussed in the context of option generation (cf. *Generating and Selecting Options,* p. 134).

Level 3 Situation Awareness

Level 3 situation awareness requires the projection of the “future actions” of the elements identified at Level 1 (cf. *Level 1 Situation Awareness,* p. 120). Recall that studies of Naturalistic Decision-Making typically examine problem-solving and decision-making in highly dynamic environments such as fire fighting. The status of Level 1 elements in such situations may change suddenly, e.g., the roof of the house may collapse or the fire may jump the fire break. Some wayfinding may, in reality, take place in such dynamic situations, e.g., the ford at the river may not be available at certain times of the day or year, or may depend on recent weather conditions, or the snow pack may not be stable and pose a high avalanche risk.

Most, if not all, research on spatial and wayfinding cognition has been conducted in stable environments, however, so there is no information on the development of Level 3 situation awareness in wayfinding or on how dynamic environmental conditions might affect spatial and wayfinding cognition. Of course, locomotional structures in the physical world are, for the most part, fairly stable. The design of electronic worlds, in contrast, offers opportunities for dynamic locomotional structures. This might be used to adapt to user behavior and simplify wayfinding, or it could (and probably is) be used to thwart wayfinding efforts, for instance, to create challenging games or learning situations.

Because of the lack of psychological evidence, the demands of Level 3 situation awareness will not be considered in this dissertation.

Generating and Selecting Options

Once the wayfinder has developed a mental representation of locomotional structure—Level 1 situation awareness, they may be use it to generate options and select among them. A solution to a wayfinding problem is a route—a path that meets the needs of the superordinate task. A partial solution, in wayfinding problem-solving and decision-making is, consequently, a piece of such a path, and an option is a piece of a path that might be a partial solution. The option generation task faced by the wayfinder is thus *route-prediction*—predicting which of the paths leading from the present location might (eventually) satisfy the needs of the superordinate task. Route-prediction, as mentioned earlier, constitutes development of Level 2 situation awareness (*Level 2 Situation Awareness*, p. 131). The option selection task is *route-selection*—selecting which of the immediately available paths to take.

According to the three models of general problem-solving and decision-making, options may be generated from the mental representation (the Problem-Space Search model) or they may be retrieved from memory (the Naturalistic Decision-Making model) or some combination thereof (the Reflective Problem-Solving model). Reasoning from the mental representation is, by the present definition, part of the wayfinding subtask. Retrieving previously acquired knowledge from memory is part of the subtask of spatial knowledge preservation. Consideration of the latter type of option generation is therefore deferred until future work, when the relationship between environmental locomotional design and spatial knowledge preservation is considered.

Although it would be possible to distinguish between factors that affect route-prediction and factors that affect route-selection, most studies do not do so. They focus on the factors that affect overall wayfinding performance or behavior and do not provide the level of detail necessary to determining attribute differences to one subtask or the other. The exceptions to this include studies that focus specifically on the criteria that might be used in route-selection (travel distance, travel time, familiarity, task priorities, etc.) [68, 209, 260]. These, however, examine how choice is affected rather than on how performance is affected. As attribution of affect to route-prediction or route-selection would, in most cases, be a matter of speculation rather than established fact, the two will be discussed simultaneously. This should not create undue difficulties, since the goal is a prescriptive rather than explanatory model.

The factors that affect route-prediction and route-selection can be divided into three categories. The first category consists of properties of the locomotional structure itself. The second category is composed of factors defined by the relationship between the superordinate task and the locomotional structure. The third category contains factors concerning relationships between the locomotional structure and other environmental structures such as perceptual and informational structures that affect the placement of information access points.

Properties of Locomotional Structure

Properties of the locomotional structure itself are the most extensively studied of the factors that affect route-prediction and route-selection, perhaps because they are the most readily quantifiable. This category has two factors both of which are related to properties of the *plan* or *layout* of the locomotional structure—the relationships among its locations and paths. The first factor is *plan complexity*, which is a combinatorial function of possible destinations, possible routes and their branch points. The second factor is *plan organization*, which is an indication of the complexity of the logic behind the spatial arrangement of locations and paths. Note that, while the terms “plan complexity” and “plan organization” are both common in the literature, they have both been used for either concept and, occasionally (although rarely) for a composite thereof. The definitions of these terms specified here were selected as being the most descriptive.

Plan Complexity

Several measurable properties of locomotional structure have been examined with respect to how well they predict wayfinding success, including the number of branch points, the number of options at branch points, distance between branch points, and the distance between potential destination locations. Neither distance between branch points [25, 57] nor distance between potential destination locations [57] have been found to be significant. Both number of branch points and number of options, however, have consistently proven significant.

As discussed earlier (*Mathematical and Computational Models of Wayfinding*, p. 115), several attempts have been made to develop mathematical models of actual wayfinding behavior. Best [25], in early work of this type, found that the number of branch points and total number of branch point options show a .93 and .97 correlation with “lostness” (unintentional deviation from a shortest path), respectively. Dada and Wirasinghe [57] developed a similar equation to account for differences in wayfinding times between subjects who were familiar with the environment and those were not. According to this equation, number of branch points is a significant factor in accounting for wayfinding difficulty. They also report on the influence of other factors. These will be discussed shortly.

Weisman [278] correlated independent judges’ ratings of abstract diagrams with self-reported wayfinding experiences in buildings whose floorplans corresponded to the rated diagrams. He found that “judged simplicity of floor plan organization,” was able to account for 56% of the variance in reported frequency of disorientation. O’Neill [203], in an ensuing study using similar diagrams, found that number of “intersections” accounted for 25% of the simplicity rating. “Intersection” seems to refer to a location at which a change of direction is possible or necessary. This differs from the present use of branch point in that, for example, a jog in a corridor would qualify as an intersection but not as a branch point. Nonetheless, a large number of intersections are branch points. Best [25] found that number of changes in direction (not at branch points), did not affect the likelihood of a subject becoming “lost” during actual wayfinding.

These results clearly show that wayfinding performance decreases as *route complexity*—the number of branch points or the number of options at branch points along a route[xliv]—increases. They also suggest that an increase in *plan complexity*—the overall number of branch points and number of options at branch points in a layout[xliv]—has a similar effect. Presumably, the latter reflects the likelihood that a randomly chosen route in a complex layout will be more complex than one selected from a less complex layout. That number of branch points and number of branch point options affect wayfinding is consistent with the supposition that the locomotional structure defines the wayfinding problems the wayfinder must solve [214], and determines how many decisions the wayfinder is likely to have to make and how complex each decision is likely to be.

Other factors, such as familiarity and signage (symbolic information added to the environment) may mitigate, but do not cancel, the effects of plan complexity [203, 205, 278]. For instance, O'Neill found that "the wayfinding performance of participants with access to signage in the most complex settings remained equivalent to, or significantly poorer than, those in the simplest settings with no signage" [203, p. 553]. Weisman found that "respondents' own familiarity with these buildings was able to account for but[xlv] 9% of the variance in frequency of disorientation data" [278, p. 189].

Plan Organization

The logical complexity of the plan layout also seems to affect wayfinding. Logical complexity, not surprisingly, is less quantifiable than combinatorial complexity. Different studies have focused on different logics that may underlie layout and how they might affect wayfinding complexity.

[xliv] Operationalizations of variables such as route or plan complexity (and hence the definitions) given here are specific to the locomotional design context. Additional operationalizations and definitions must be considered in other contexts, e.g., informational design.

[xlv] Used in the sense of "only."

<u>Logics Underlying Plan Organization</u>

In addition to the “intersections” criterion for judged simplicity of floor plan organization (discussed in the previous section), O’Neill [203] found that “symmetry” accounted for 32% of the simplicity rating. He also asked judges to rate the diagrams on “legibility” (ease of understanding). “Ease of description” accounted for 34% and “symmetry” for 20% of this rating. He found evidence, during actual wayfinding, that the rate of travel was disproportionately faster for symmetric than for non-symmetric layouts, but does not show similar anomalies in number of wrong turns or amount of backtracking. (The other factors that O’Neill found to account for judges’ ratings were, for simplicity, “familiarity” (20%) and “number of segments” (12%), and, for legibility, “number of turns” (20%) and “enclosure of space” (17%). He does not highlight any of these characteristics in discussion of the behavioral results.)

Passini, drawing on his extensive observations of wayfinding behavior, found *spatial organization*—“the principle by which an order among various inside spaces and architectural elements is established” [214, p. 130]—to be the single most important environmental characteristic affecting subjects’ general difficulties in processing spatial information [210, 214]. O’Neill’s “symmetry” and “ease of description” are clearly related to spatial organization.

Furnas [80, 81] offers a theoretical exploration of some of the properties of abstract information structures that affect their navigability. In the course of this exploration, he describes the *logical structure* of the information, that is, the logic by which elements of the information structure are related. He then discusses ways in which different locomotional structures may be derived from different logical structures to make navigation more efficient, e.g., adding a tree structure to a linear list. He also discusses the implications of different logical structures for informational design.

O’Neill, Passini and Furnas offer three different types of *plan organization*—how locations and paths are organized with respect to each other. While plan organization may be entirely random, most follow some underlying principle. O’Neill describes a organization based on Euclidean geometry, Passini one based on a combination of geometry and function, and Furnas one based on the semantics of the information content. Plan organization establishes a frame of reference by which the wayfinder may reason about the relationship between their current location and their destination, aiding both route-prediction and route-selection. This suggests that the complexity of the logic of plan organization determines the complexity of the reasoning necessary to route-prediction and route-selection. For instance, metropolitan areas that are laid out on a grid, such as Manhattan, are generally regarded as easier to navigate than those with less geometrically regular layouts, such as Boston.

The type of spatial knowledge called spatial schemata (cf. Chapter 2, *A Design-Oriented Model of Navigation as a Cognitive Task*, p. 58) can be understood as knowledge of plan organizations common to a given type of environments, e.g., a river valley, an office building or a restaurants. Gross and Zimring report that subjects used such standard organizations when drawing hypothetical floorplans of buildings of which they were shown photographs only of the exterior [101]. "At a global level, schemas describe overall plan topology and geometry and major building features ('parking garage in the basement levels'; 'in a department store cafeteria will be on the top floor'). More local schemas describe typical partial organizations of building elements ('fire stairs at the ends and middles of corridors'; 'coin-operated telephones will be near the rest rooms')" [101, p. 371].

Plan Organization and Behavior

Although plan organization can be based on different types of logic, most studies that seek to determine or quantify its effect on behavior and performance have focused on geometric organization. Evans et al. [73] found that a rectangular grid structure enhanced the accuracy of route learning. Although they did not show whether it improved wayfinding performance, this would be in accordance with O'Neill's result that symmetric layouts produced faster rates of travel (see *Logics Underlying Plan Organization*, p. 137).

Peponis et al. [217] defined an *integration value* that measures the accessibility of a location. This measure is based on the "least number of spaces that must be traversed from each space to all the others." They found a high correlation between the integration values of branch points and their frequency of use, with highly integrated—i.e., easily reached from many locations—branch points being used more frequently. They also found that people tended to bias wayfinding search to follow *integration cores*—paths comprising highly integrated branch points. This result is consistent with McCormick's [181] recommendation, based on observed wayfinding behavior, to develop a "central trail" to integrate and indicate main traffic routes in hospitals.

In the equation developed to account for differences in observed wayfinding performance (see *Plan Complexity*, p. 135), Dada and Wirasinghe [57] incorporate a term for "level changes" that represents branch points, such as elevators or stairs, where the locomotional structure branches vertically rather than, or as well as, horizontally. This factor was ten times as important as normal branch points to wayfinding difficulty. Note that "level changes" can conceivably be generalized to discontinuities of any type in the plan organization. Such could be introduced by the intersections of locomotional structures defined by different locomotional mechanisms (e.g., car to train), or by other divisions (e.g., private car vs. public bus, or surface streets and freeway systems). The effect of organizational discontinuities on spatial knowledge preservation, wayfinding behavior or wayfinding performance has not been studied, and so can only be noted here as presumably affecting wayfinding performance negatively.

Plan complexity and plan organization are clearly different properties of a locomotional structure. There is no evidence on whether one has a greater effect on wayfinding performance than the other. Lawton [164] found differences in the degree to which men and women attend to and reason about information regarding plan organization, so it is possible, and even likely, that their relative importance depends factors such as characteristics of the individual wayfinder. Kerr [143] showed that subjects' conceptions of the organization of a database affect wayfinding performance, and that this was a more significant factor than visual information design. This suggests that, regardless of their relative significance, wayfinding difficulties due to a complex plan layout can only be alleviated, and not eliminated, by informational design.

Relationships between Task and Locomotional Structure

Route-prediction constitutes the development of Level 2 situation awareness and requires mapping the destinations and routes dictated by the superordinate task to the locomotional structure offered by the locomotional design. This indicates that certain relationships between the superordinate task and the locomotional structure might affect wayfinding. Such effects have received limited attention in studies of wayfinding in physical environments, but have garnered more interest in studies conducted in electronic settings. These studies show that two relationships, in particular, appear to be significant: the relationship between the locations and paths that are necessary to task execution and the overall locomotional structure, and the relationship between the logic of the task and the organizing principle of the locomotional structure.

Task-Defined Structure

The fundamental purpose of wayfinding is to enable the wayfinder to reach some location or travel some path so that they can carry out some superordinate task [67]. This task defines a set of destinations and routes, and dictates certain relationships among them, that is, it defines a locomotional structure. The locomotional structure dictated by the task is here called the *task-defined structure.* As the task-defined structure is defined by the needs of the task, there is no guarantee that it matches the actual or even the perceived locomotional structure offered. For instance, a visitor to Paris might wish to see the Bastille, however, this does not mean that the Bastille will be resurrected. Of course, if the task is to succeed, there must be some resemblance between the task-defined structure and the actual locomotional structure. Route-prediction is the process of mapping the task-defined structure to the perceived locomotional structure. Route knowledge is the preserved form of such mappings.

Studies on wayfinding errors show that mismatches between the task-defined structure and the actual locomotional structure are one source of wayfinding error [25, 31]. If, as is assumed here, the perceived locomotional structure is a correct approximation of the actual locomotional structure, evidence that pertains to mismatches between task-defined and perceived locomotional structures can be assumed also to pertain to mismatches between task-defined and actual locomotional structures. A variety of studies shows both the importance of the task-defined structure and effects of its relationship to actual locomotional structure.

The first step in understanding the relationship between task-defined and actual locomotional structures is to understand the task-defined structure. The importance of understanding the task-defined structure to wayfinding design is evidenced by Passini's "Guideline to Wayfinding Design" [213] (see Chapter 2, *Romedi Passini: Wayfinding in Architecture*, p. 87). The first five (of seven) steps in this process are aimed at identifying the task-defined structure associated with the most common and/or important tasks performed in the environment. These steps include 1. identifying key destinations, 2. developing user profiles, including special access needs, 3. identifying the wayfinding conditions—the circumstances under which wayfinding takes place, 4. identifying wayfinding problems that are critical due to special user needs or special circumstances, and 5. identifying the best solutions to those wayfinding problems, i.e., routes for users to take to travel between destinations. (The last two steps of the Guideline then aim at developing an informational design to compensate for mismatches between the task-defined and actual locomotional structures.)

In detailing the third step, Passini describes three possible wayfinding conditions that predictably affect route desirability. Under *emergency conditions,* e.g., in a fire or flood situation, the primary considerations are speed and safety. Under *recreational conditions,* e.g., when sightseeing or touring, the primary consideration is the experience of the journey, although safety and, ultimately, reaching the destination (or completing the journey) are still concerns. Between emergency and recreational conditions lies *resolute conditions,* in which getting to the destination is a priority, but speed may not be a pressing concern, e.g., when shopping, finding a restaurant, getting to work, etc. These distinctions and Passini's inclusion of them suggests that the task-defined structure is defined not only by the task, but also by the circumstances under which it is performed.

Watts [277], studying spreadsheet users, observed that users "invested time and energy into the initial arrangement of information so they could avoid navigating" [277, p. 311]. They did this by (temporarily) copying information so that related information was visible simultaneously, and by dedicating certain (fixed) locations to specific information. In other words, users, taking advantage of the flexibility of the environment, adapted the actual locomotional structure to the task-defined structure manually. This *cost-structuring* [43, 231] behavior is also reported by Card et al.: "Users constantly rearrange their environments to *tune* the relative costs of the information, so as to make them efficient" [43, p. 112].

Wright and Lickorish [287] studied the selection of navigation options for a task that involved locating and comparing information in a computer document. They found that subjects "do not necessarily select the navigation procedure having the fewest actions, but they are likely to select the procedure that requires less cognitive computation time" [287, p. 986]. The discussion shows that "less cognitive computation time" is a result of a closer match between task-defined and locomotional structures, e.g., price listings by vendor rather than product in a multiple-item comparative shopping task. In this case, the task-defined structure was often dictated by the strategy chosen by the subject to complete the task and was not inherent in the task itself (although the set of likely strategies was small and predictable).

Norman and Chin [200] found that the structure of a hierarchical menu had a significant effect on search performance, with different structures being more effective for different types of search tasks. Specifically, they found that a tree structure with many choices at the top and few in the middle improved performance considerably when the target was specified by descriptive criteria. Tree structure had less influence when the target was named explicitly, although a structure with fewer choices at the top and many at the bottom offered slightly better performance.

Wright and Lickorish [286] compared navigational performance in a hypertext system with embedded links to one with a separate page of links (organized as a table of contents). They conclude, "these data strongly suggest that authors need to bear in mind both the structure inherent in the content material and the tasks readers will be seeking to accomplish when they are designing navigation systems for hypertexts" [286, p. 93]. Unfortunately, they do not describe clearly what properties of tasks might suggest what types of locomotional structures.

Several designs have been proposed that, in effect, adapt the actual locomotional structure dynamically to accommodate task needs. Boyle and Snell [29] use knowledge-engineering techniques to adapt a hypertext link structure in response to user queries, creating shortcuts that bypass "uninteresting nodes." da Silva et al. [56] hide or reveal links in a hypertext structure in order to create paths through the structure in order to accommodate the user's presumed level of understanding. Unfortunately, neither of these systems seems to have been subject to empirical testing to demonstrate their efficacy. It is interesting to note that most examples of adapting locomotional structure to accommodate task needs seem to be in the domain of hypertext. This may be because the emphasis of hypertext on the node-link structure brings locomotional structure to the forefront of design considerations.

These results suggest that navigational performance is improved by a closer correspondence between the task-defined and actual locomotional structure. Presumably, this is because unnecessary options and decisions are eliminated and because the most recently perceived portions of the actual locomotional structure are relevant to the immediate decisions necessitated by the task. The results also show that the appropriate task-defined structure may depend not only on inherent characteristics of the task, but also on the conditions under which it is performed and on the strategy selected by the user to perform the task.

Task Logic

The task-defined structure, like other locomotional structures, may be organized according to some underlying logical principle. Its organization may be driven by logical or temporal sequencing of subtasks, e.g., checking luggage, passing security, buying coffee, waiting at the gate, and then getting on the plane. It may also be driven by the semantics of the conceptual environment, e.g., according to classification taxonomies such as Linnaeus' classification of plants and animals based on morphology and physiology, or Dewey's classification of books according to subject matter. Although there are no behavioral studies of the effect of this relationship between the task logic that organizes the task-defined structure and the organizing principle of the actual locomotional structure, it can be presumed to affect wayfinding performance. This presumption is supported by a small number of theoretical considerations.

Furnas [80, 81] describes several characteristics that the organizing principle of the locomotional structure must exhibit if a wayfinder is to be able to find their way in a large and complex information structure without reference to preserved spatial knowledge. The import of these characteristics is that the organizing principle must be discoverable and computable within the limits of human cognition. He does not mention the relationship between task logic and organizing principle explicitly. However, he implicitly assumes that the task-defined and locomotional structures differ and that the role of informational design is to provide a mapping between them that is meaningful in terms of task logic (as represented by informational semantics). He also asserts that, in order for the informational design to fulfill this role, such a mapping must be possible, that is, that the organization of actual locomotional structure can be described in terms of logic that is meaningful to the task.

This requirement of a correspondence between organizing principle and task logic is reflected in the recommendations of McCormick [181] and Peponis et al. [217] for "central trails." These structure floor plans to reflect the functional organization and priorities of public buildings such as hospitals.

Presumably, correspondence between organizing principle and task logic allows the wayfinder to "reuse" the thinking required by the task in making wayfinding decisions. Correspondingly, discrepancies add an additional step in the process of relating destinations and routes to locations and paths.

Information Access Points and Locomotional Structure

Information plays a key role in problem-solving and decision-making, and the acquisition of environmental information is a critical step in developing a mental representation. Information access points—locations at which information becomes perceptually available—and their relationship to the mental representation was discussed earlier (see *Information Access Points*, p. 128). The information provided at information access points determines what information is available. The placement of information access points, however, determines when it becomes available. Both factors affect what is represented mentally at any given point in time, which, in turn, affects both what options may be generated as well as which is selected. The information provided is largely a matter of informational design, whereas the placement results, in part, from environmental locomotional design.

“Placement” of information access points is subject to two interpretations. First, placement can be considered in spatial terms, referring to the spatial relationship between an information access point and its associated branch point. Second, it can be viewed temporally, referring to the temporal relationship between the two that is established by locomotion. The spatial placement of an information access point is a property of the relationship between locomotional structure and two other types of environmental structure, informational and perceptual. The temporal placement of an information access point is a property of the relationship between movement (namely, possible speed of movement) and the spatial placement of the information access point. Examination of the (limited) literature surrounding these relationships also reveals that certain types of information access points may have greater influence on problem-solving and decision-making and are more controllable through environmental locomotional design than others.

Informational and Perceptual Structures

Burns, in his study of causes of wayfinding errors while driving [31] (see Chapter 2, *Burns: Errors in Wayfinding*, p. 80) found that 83% of errors were related to “signs/information.” This category included “inaccurate directions and a lack of signs, obscured signs, badly placed signs, insufficient information on signs, damaged signs and confusing signs” [31, p. 212-213]. Of the five most frequent causes of wayfinding errors, irrespective of general categories, “lack of sign” accounted for 25% of errors, and “obscured signs” for 12%. (The remaining three causes were: “distracted attention,” 14%, “road repairs,” 13%, and “inaccurate directions,” 11%.) He also reports that the most frequently reported of 16 wayfinding problems were “saw a sign too late,” “missed a sign,” and “saw turn too late.” (The least frequently reported of the 16 were “misinterpreted directions,” “got lost,” and “the route was shorter than expected.”)

Dada and Wirasinghe [57], based on the equations modeling wayfinding performance in terms of branch points (see *Plan Organization*, p. 137), developed a *Visibility Index*—a measure of how well connected visually a location is to other locations. This measure is analogous to the integration value developed by Peponis et al. [217] (see *Plan Organization*, p. 137), but subdivides paths at pertinent information access points rather than at branch points. For example, a path that crests a hill would be divided at the crest, where new information comes into view, regardless of whether the road divides at that point. Buildings in which people had high wayfinding difficulty were reported to have low Visibility Indices.

Most research on information in wayfinding concerns visual information. Passini and Proulx [215] studied how information use during wayfinding differed between congenitally blind and sighted subjects. They found that the congenitally blind made substantially more decisions during wayfinding. Locating architectural elements that mark branch points, such as doors, constituted a major source of these additional decisions. Passini and Proulx also report that the visually impaired subjects used significantly more information to make the same journey, and that they relied on different types of information. In particular, the visually impaired subjects reported using auditory, olfactory and textural information not reported by the sighted subjects, and did not report visual information, such as signage, reported by sighted subjects. For example, "small features, such as a radiator, a doorframe, or an ashtray, that went unnoticed by the sighted wayfinder were shown to be important reference points for the blind traveler" [215, p. 243].

These results show that information access points depend on three factors. First, an information access point, by definition, must be associated with at least one information point—a location at which information is present. (Note that an information point need not be associated with any information access points, in which case it is useless.) Second, an information access point depends on perceptual "connectedness" between locations, specifically, between the information point and the information access point. Third, if the wayfinder is to make use of the information access point, they must be able to get to it, so the information access point must be located within the locomotional structure. The spatial placement of an information access point is thus determined by the intersection of the locomotional structure, the structure of information and the perceptual structure (of the modality corresponding to that of the information offered) of the environment.

Note of course, that the perceptual design may, at any given time, be subject to modification by environmental conditions and that this may change both content and spatial placement of an information access point or eliminate it altogether. For example, reduced visibility due to fog or darkness may prevent seeing the highly informative view from the top of the hill. Burns [31] attributes 21% of wayfinding errors to such situational factors.

Movement

While the spatial relationship between an information access point and its associated branch point determines where information becomes available, the temporal relationship between them determines how much time is available to make use of it. This is substantiated by Burns' findings that two of the most frequently reported wayfinding problems were related to the timing of information acquisition ("saw a sign too late" and "saw turn too late"). The temporal placement of an information access point depends not only on its spatial placement, but also on how fast the wayfinder is able to move. Speed of movement is a property of the steering design (which is, of course, limited by the underlying physics of movement). Thus, the time available to make a decision depends, in part, on the relationship between movement—as mediated by the steering design—and the locomotional structure.

Natural and Synthetic Information

The formula developed by Dada and Wirasinghe [57] for computing the Visibility Index for a location (cf. *Informational and Perceptual Structures*, p. 146) does not consider all information access points to be of equal value. Information access points that result from signage are weighted less heavily than those that offer direct views of destinations, i.e., are counted as offering a weaker visual connection. This suggests a distinction between *natural information*—information that results from the *perceptual design* (the design of sensory stimuli and their behavior) and characteristics of objects in the environment—and *synthetic information*—descriptive information deliberately added to the environment. Thus, *natural information access points*—information access points that provide access to natural information—seem to improve wayfinding performance more than *synthetic information access points*—information access points that provide access to synthetic information.

Note that the ultimate focus of Passini's work [210, 213] is on the development of synthetic information access points. The last two steps of his design "Guideline" (cf. *Task-Defined Structure,* p. 141) are entirely devoted to the identification and creation of visual information access points. The sixth step classifies branch points according to whether and how of the much information that is necessary to making a decision at that point is available naturally. The seventh and final step determines where signage should be placed in order to create synthetic information access points for branch points that lack sufficient natural information access points.

Executing Options and Monitoring Results

The final step in the problem-solving and decision-making process is option execution. An option, in wayfinding, is a piece of a route. "Executing" an option entails moving through the environment along the paths that correspond to that piece of route. This requires matching the conceptual representation of the option to actual environmental features, actually moving and controlling movement. The first of these activities is part of the wayfinding task, the latter two part of locomotion. Monitoring results of option execution requires monitoring the actual locomotion—making sure that movement had the intended effect. It also entails determining whether the path that is followed is, in fact, part of a route, i.e., that progress has been made toward solving the wayfinding problem. Whereas monitoring movement is part of the locomotion task, monitoring route "success" is part of the wayfinding task. The wayfinding activities involved in matching environmental and conceptual features for the purpose of executing options and monitoring the results are here called *route-following*.

Route-following can be accomplished in several ways. Observed environmental features can be matched to features contained in a route description retrieved from memory or obtained from external sources. Since the route description is expected to be valid (i.e., it describes an actual route), if actual features match the expected features, it can be assumed that progress has been made. Progress can also be evaluated directly by interpreting environmental cues directly, e.g., objects in the physical world appear larger as spatial distance to them is reduced, traffic increases around populated areas. This approach entails matching environmental features either to survey knowledge (e.g., "the town square is next to the cathedral, so moving toward the cathedral towers is the same as moving toward the town square") or to knowledge contained in spatial schemata (e.g., "the number of light-controlled intersections increases near areas with many pedestrians, such as downtown areas").

Either approach to route-following entails matching environmental and conceptual features. Note that this type of matching differs from the type of matching required by path-identification. Path-identification entails recognizing that an environmental feature *is* a location or path without necessarily identifying which specific location or path it is—category recognition, in psychological terms. Route-following entails recognizing that an environmental feature matches the mental conception of particular object—object identification or recognition in psychological terms. For example, recognizing the trail may be a matter of seeing changes in vegetation (or observing lack thereof), while recognizing which stretch of trail it is may be a matter of recognizing "the rock that looks like a stork." Not surprisingly, the majority of factors that affect route-following performance are components of informational design. However, one aspect of environmental locomotional design, route complexity, seems to influence route-following.

Streeter et al. [261] studied the effect of different representations of route descriptions on route-following while driving. They compared verbal directions (presented via tape recorder operated by subjects) to graphic directions (the route drawn on a map read by subjects). They report, "[t]ypical errors were passing the destination, turning in the wrong direction, and turning onto the wrong street." [261, p. 556]. Although subjects committed fewer errors (and were faster) when given verbal directions, subjects in both conditions committed these types of errors.

Burns [31] similarly reported that the 16 most frequently reported wayfinding problems while driving included "turned in wrong direction," "turned before you were supposed to," "chose the wrong lane," "drove past your destination," "went off planned route," "found an unexpected turn," and "passed the correct exit off roundabout." These seven errors lie between the top and bottom three, in frequency, as described earlier (see

Information Access Points and Locomotional Structure, p. 145). (The remaining three problems were "route longer than expected," "doubts about route," and "had inaccurate directions.")

All of these errors relate to route-following difficulties caused by the presence of locations and paths that are not part of the route. That is, it is not possible to turn onto the wrong street if there is no street there to turn onto. Even turning in the wrong direction, which is likely to be attributed to poor spatial ability or directional dyslexia (difficulty in interpreting symbolic directional cues), is not possible if there is no street to be turned onto. They could also be attributed to difficulties in steering, i.e., intending to turn in the correct direction, but turning the steering wheel in the wrong direction. However, this seems more likely to be corrected immediately (without incident), or be reported as an accident rather than as a wayfinding error.

O'Neill [204] studied the relationship between route complexity and route-following performance. His results indicate that errors (number of wrong turns) increase and performance (time to destination) decreases as route complexity increases. However, his focus was on wayfinding as mediated by cognitive maps, so routes were learned from photographs and were followed from memory. It is thus not clear whether the errors committed are errors of recognition due to ambiguous environmental information (e.g., two branch points appearing similar in the photographs), errors of learning or memory retrieval, or whether they are route-following errors as described here. Therefore, while these results are not conclusive, they do seem to affirm a relationship between route complexity and route-following difficulty.

Relationship between Steering Design and Locomotional Structure

In addition to affecting wayfinding performance by manipulating elements of environmental locomotional design that affect wayfinding subtasks, it may be possible to affect wayfinding performance by manipulating elements to alter the number of wayfinding subproblems encountered. Passini and Proulx [215], in the study on wayfinding by congenitally blind individuals (cf. *Information Access Points and Locomotional Structure*, p. 145), identify two other sources of increased decision-making by the visually impaired subjects. The first of these is related to maintaining direction when following a corridor or traversing an open space. The second is related to the use of stairs and consists of such behaviors as finding the handrail, transferring from one flight of stairs to another, and identifying the beginning and end of stairs.

These types of decisions suggest that the relationship between the steering design and the locomotional structure affects wayfinding. Although it does not seem to have been studied explicitly, common experience would suggest that the fewer steering actions required to remain within the locomotional structure, the less likely it is to deviate from that structure. That is, the fewer degrees of freedom left to the user's control, the easier it is to follow the locomotional structure. For example, the steering design of trains includes means for assisting them to stay on the rails. The steering design of cars has no analogous provisions to help them stay on the road.

Note that deviation from the locomotional structure is only possible in environments in which the spatial environment and the locomotional structure are not identical. E.g., in the physical world, roads define a locomotional structure for cars. The steering design of cars allows them to deviate from this locomotional structure, generally to the detriment of the car or its occupants. Such deviation is not possible in traditional hypertext systems where it is not possible to go beyond the limits of individual nodes.

Key Elements of Environmental Locomotional Design

Analysis of the literature on spatial knowledge revealed that three elements of environmental locomotional design are critical to the necessary mental representation. Two of these, locations and paths, are basic elements, while the third, branch points, emerges from relationships among the first two. A fourth environmental feature, information access points, was shown to be significant in the development of a mental representation, but not represented explicitly. Information access points are not elements of environmental locomotional design proper, but rather emerge from relationships between environmental locomotional design and other aspects of design. The analysis shows that a number of elements, such as landmarks, nodes and districts, that are critical in general spatial cognition, are elements of informational rather than locomotional design and serve to organize spatial knowledge rather than to affect spatial problem-solving and decision-making.

A set of locations and paths along which movement is possible constitutes a locomotional structure. Locomotional structure was found to be the first of four features of environmental locomotional design that affect wayfinding performance. A locomotional structure is defined by and with respect to a particular locomotional mechanism or means of effecting movement. Locomotional mechanisms, in turn, are limited by environmental physics—the rules that govern interactions between matter and energy—whether real or metaphorical. The locomotional structure offered by an environment defines the wayfinding problems that must be solved in that environment. Two properties of locomotional structure affect wayfinding particularly. First, the plan complexity—the number of branch points and the number of options at branch points—determines how many decisions the wayfinder is likely to have to make and how complex each decision is likely to be. Second, the plan organization—how locations and paths are organized with respect to each other—determines how complex wayfinding reasoning needs to be.

The second feature of environmental locomotional design that was found to affect wayfinding is the relationship between the superordinate task and the locomotional structure. Two characteristics of this relationship, in particular, affect wayfinding. First, the similarity between the task-defined and the locomotional structure determines how many irrelevant elements the wayfinder might have to consider. Second, the similarity between the task logic and the underlying organizing principle of the organization of the locomotional structure determines how much reasoning the wayfinder has to do to understand the relationship between the two and map one to the other.

The third feature of environmental locomotional design that was found to affect wayfinding is the spatial and temporal placement of information access points—locations at which information is perceptually available. Spatial placement is fundamentally determined by the relationship between the placement of information points—a property of informational design, perceptual structure—a property of perceptual design, and locomotional structure. Temporal placement is a function of movement and spatial relationships between information access points and their associated branch points. Information access points that depend on naturally occurring information were noted to have greater influence on wayfinding than those that depend on synthetic augmentation of the environment, e.g., through signage.

The fourth feature of environmental locomotional design that was found to affect wayfinding is the relationship between steering design and the locomotional structure. This feature only comes into play in environments where deviation from the locomotional structure is possible. If the steering design permits deviation from the locomotional structure, wayfinding problem-solving and decision-making must consider demands of the locomotional structure that the steering design appears to make available as well as the demands of the actual locomotional structure. This may result in unnecessary iterations of the problem-solving and decision-making process.

"Point" vs. "Region": Going from Psychology to Design

The psychological literature analyzed to identify key elements of environmental locomotional design and expose relationships between these and wayfinding cognition makes liberal use of terms such as "point" and "linear." For instance, landmarks are typically considered to be "point" elements [96, 172, 222]. The elements thus described are, of course, not "points" or "lines" in the geometric sense as they have extent in two or more dimensions. The geometric connotations may be warranted in the psychological literature as these elements often serve as spatial referents and simplification as a point or line is sufficient [222, 232]. From a design perspective, such simplification is not only misleading, but masks important properties that must be considered.

For example, both types of decision "points"—branch "points" and information access "points"—are, in fact, contiguous regions of space with more or less clearly delineated boundaries. These regions constitute a set of contiguous locations at which the same locomotional options are available. For instance, an intersection is a typical branch "point." During locomotion, there is a "point" in both time and space at which one "enters" the intersection—the moment and location at which turning is first made possible. There is also a "point" at which one "exits" the intersection—the moment and location at which one or more of the locomotional options are lost. If the entry and exit "points" are not identical, decisions may be executed at any one of a contiguous series of locations. Similarly, for an information access "point," there is a moment and location at which the information first becomes perceptible, a moment and location at which it ceases to be accessible and, potentially, a contiguous series of locations from which it may be perceived.

To a designer, who is defining branch and information access "points" and manipulating their properties, these distinctions are critical. Because of this, the word "region" will be used in place of "point" when discussing the design elements. Thus, *decision region, branch region,* and *information access region* will be used in place of decision point, branch point and information access point, respectively. A series of contiguous locations at which entry or exit from a region is possible is generically referred to as a *port,* and, specifically, as a *region entry port* and *region exit port*, respectively.

This refinement of "points" into "regions" and "ports" invites several observations that are immediately relevant to design. First, many decision "points" that are considered to be single entities from a psychological perspective may actually comprise several decision "regions" when considered from a design perspective. For instance, an intersection may initially offer the three options of "left," "right," and "right-and-three-quarters," but as the wayfinder moves through it, a point may be reached where, for example, the "left" option is no longer available. It is thus possible that the intersection branch "point," in actuality comprises two branch "regions": a region offering the options {left, right, right-and-three-quarters} and one offering only {right, right-and-three-quarters}. (Note that "singleton" branch regions are not possible; a region must offer at least two locomotional options or it is not a branch region.)

Second, all ports are located on region boundaries. Third, although, by definition, it is possible to move to any location within a given decision region (else it wouldn't be possible to obtain its information or execute a decision), there may be portions of the boundary that are not part of any port. Fourth, the determination of entry and exit ports depends on the direction of movement. Fifth, entry and exit ports may not be identical, that is, a location that permits entry may not permit exit (and vice versa) even if movement is reversible. Even if entry and exit ports overlap, their limits may differ.

Note that a similar refinement may be undertaken for “linear” elements such as paths, but has not proven necessary, thus far. It may, however, prove necessary at some future time. Understanding of informational design, for instance, may require being able to distinguish between different “sides” of a path, and steering design may necessitate being able to distinguish lateral path boundaries.

Going from Design of Physical Environments to Design of Electronic Environments

The preceding discussions of navigation and navigational design (Chapter 2) and of wayfinding and environmental locomotional design (this chapter) rely heavily on evidence from design of physical environments. As the present work is aimed specifically at the design of electronic environments, it is useful to consider how design of electronic environments differs from design of physical environments. Brief reflection yields two major sources of differences. There may, of course, be others.

Invariant Constraints in Physical Design

First, design of physical environments is subject to at least three sets of invariant constraints that are inappropriate to electronic design (although some electronic environments may choose to simulate their effects). The first set represents constraints imposed by natural physics on interactions between matter and energy. These constraints include forces that operate on moving and stationary objects such as gravitational and inertial forces. They also include constraints concerning the preservation of matter and energy, in particular, “nothing comes from nothing.” These constraints dictate, for example, that objects cannot suddenly appear in or disappear from the environment, that objects cannot be present in two different locations at once and that instantaneous movement is impossible.

Part of the design of an electronic interaction environment is to define the laws of "physics" (or lack thereof) that are to operate in that environment. Design of tools based on such an environment always has the option of overriding or redefining the "physics" it provides. Thus, for example, armies can appear from nowhere in electronic games, a file can be present simultaneously in a folder, a document window and a menu, and hypertext link traversal can be virtually instantaneous.

Design of physical environments must also accommodate constraints imposed by human biology. For instance, a human cannot fit through the eye of most needles, cannot survive high impacts or gravitational forces, cannot alter itself and is limited to a single field of vision. In the design of electronic environments, in contrast, humans can be provided with any and all imaginable attributes. These may be implicit and only apparent by their consequences or they may be explicitly modeled, e.g., by avatars. This allows for science-fiction-like biologies with alien abilities such as shapeshifting, x-ray vision and immortality.

The third set of constraints to which design of physical environments is subject is that of Euclidean geometry. Euclidean geometry dictates that the shortest distance between two points is a straight line, that parallel lines never intersect and that two points cannot occupy the same location unless they are identical. Design of electronic environments is free to employ other types of geometry, including defining new ones. This allows environments to exhibit geometric properties not possible in the physical world. For instance, Tromp and Dieberger [271], examining a "Multi User Dungeon" (a networked electronic game), revealed several phenomena that were inconsistent with Euclidean geometry. "Missing rooms" are "rooms one would logically expect when drawing a map of interconnected rooms in a 2D or 3D grid, but which do not exist," "overlapping rooms" are rooms "occupying the same space on the grid but nonetheless representing two exclusive spaces," and "magic mazes" are "spaces where we could go through an exit (for instance) and retrace our steps … only to find ourselves in a completely different room" [271, p. 189].

Computational Nature of Electronic Environments

The computational nature of electronic environments is the second major source of differences between design of physical and electronic environments. It allows both environment and tools to appear "intelligent," that is, to exhibit the capacity to acquire and apply knowledge. Objects in an electronic environment may, potentially, "perceive" their surroundings, "reason" about it and respond in accordance with that reasoning. This allows environment and tools to interact with users providing them, for instance, with information tailored to the specific context. A physical train schedule, for example, must of necessity list all trains leaving from a particular station, even if the user only needs to know about the "next" train to their destination. An electronic train schedule, in contrast, can be programmed to provide only and exactly that information, and may even provide additional useful information that might otherwise be difficult to be obtain, e.g., "the next train to Destination F leaves at 9:23, however, you may board the express train leaving at 9:12 and change trains at Destination C for an earlier arrival at Destination F."

The computational nature of electronic environments allows their behaviors and actions to be configured or adapted dynamically to accommodate the needs of specific individuals or groups of individuals, to respond differently to different user behaviors and to take situation or task dynamics into account. Electronic environments and tools may even negotiate with users in order to accommodate user needs better. They may also be modified structurally to anticipate user needs. This latter characteristic is particularly important to environmental locomotional design; in the physical world, "not much can realistically be done to change the road geometry" [31], whereas, in an electronic environment, changing "road" geometry is quite easy—the difficulty lies in knowing how it should be changed.

Implications for Design

The two major differences between design of physical and electronic environments interact. Freedom from the constraints imposed on physical environments offers unprecedented opportunities for exploring new ways of conceiving of and interacting with life, the universe and everything. The computational nature of electronic environments offers the means for taking advantage of these opportunities. However, electronic environments must be designed and programmed explicitly to realize this potential. This requires understanding constraints that apply to both physical and electronic environments as well as constraints that apply only to electronic environments.

The present work is aimed at the former understanding: assuming that human cognition has evolved in response to the physical environment and is stable over an extended period—say, several human generations, at least—the work assumes that fundamental cognitive needs are the same in both types of environments. An interesting consequence of the differences between physical and electronic environments is that it may change the relative difficulties of or efforts required for different tasks, and may change the consequences of error. For instance, in the physical world, the effort required for locomotion often outstrips the effort required for information-gathering, e.g., when making a turn at an intersection. In electronic environments, in contrast, the relative costs of the two tasks are reversed, with information-gathering generally requiring far more effort than locomotion. While the present work does not examine such differences directly, it offers designers the knowledge needed to manipulate the effort required for the wayfinding task.

Summary

This chapter has completed the first two steps of the design knowledge development process for understanding wayfinding as a problem in environmental locomotional design. It first developed a design-oriented model of the cognitive task of wayfinding by drawing on models of the cognition of general problem-solving and decision-making, and empirical evidence of wayfinding behavior. It then used this model to guide analysis of the psychological literature on wayfinding in order to expose key relationships between wayfinding performance and environmental locomotional design and identify features of environmental locomotional design that affect wayfinding.

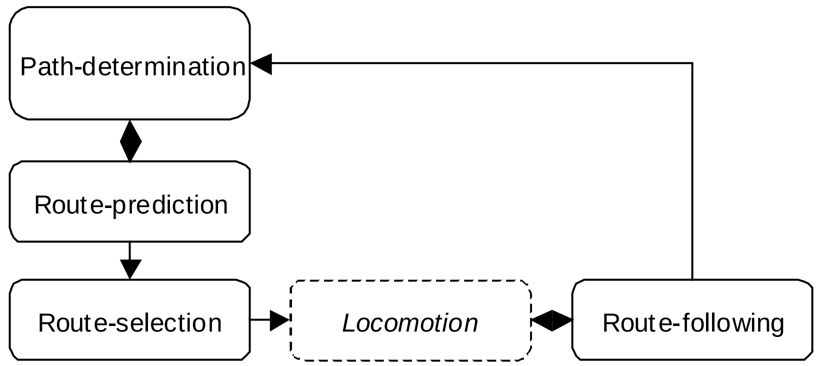


Figure 20 Design-oriented model of wayfinding.

The design-oriented model of wayfinding comprises the four subtasks of path-identification, route-prediction, route-selection and route-following (Figure 20). Path-identification represents the development of a mental representation necessary to solve wayfinding problems and requires recognizing locations and paths in the environment. Route-prediction represents the generation of possible options for locomotion. It requires mapping destinations and routes—locations and paths defined by task goals—to those observed in the environment, in order to predict which of the immediately available paths would serve task needs. Route-selection requires selecting one from among these. The selected option is then executed by moving along the selected path. While actual movement and controlling movement are subtasks of the locomotional task, it requires matching specific environmental elements to elements in the mental representation. This matching is also required during the final step of the model, route-following, which is the evaluation of whether progress has been made toward solving the wayfinding problem.

This design-oriented model was then used to guide an analysis of the literature on spatial and navigational cognition, aimed at identifying what elements of environmental locomotional design affect wayfinding and exposing the relationships between these elements and wayfinding performance and behavior. This analysis revealed four features of environmental locomotional design that are significant in wayfinding cognition: locomotional structure, the relationship between the superordinate task and locomotional structure, the spatial and temporal placement of information access points and the relationship between steering design and locomotional structure.

A brief consideration of the differences between design of physical and design of electronic environments discussed two major sources of differences. The first of these is constraints that are invariant in physical design, but inappropriate in electronic design—laws of natural physics, limitations of human biology and restrictions of Euclidean geometry. The second source of differences is the malleability of electronic environments due to their computational nature. These two types of differences conspire to imbue electronic environments with great potential; however, they also impose new requirements for design and development. One of these requirements is understanding basic human cognitive needs.

Development of the design-oriented model of wayfinding and detailing of the relationships between wayfinding cognition and environmental locomotional design represents expository analysis of psychological knowledge. Identification of the key elements of environmental locomotional design represents the beginning of interpretive synthesis converting this knowledge into design knowledge. This synthesis resulted in refining the definitions of design elements that are treated as "points" in the psychological literature into a more complex concept of "regions" with discrete entry and exit "passes," exposing differences in the needs between psychology and design. The process of synthesizing design knowledge from psychological is completed in the following chapter, where the relationships between wayfinding and environmental locomotional design described here are reformulated as principles for design and applied to actual design examples.

CHAPTER 4
Design Principles

Think left and think right
and think low and think high.
Dr. Seuss, *Oh, the THINKS You Can Think!* [xlvi]

The previous chapter reviewed the existing empirical evidence describing the relationships between wayfinding and environmental locomotional design. This yielded a great deal of information about the constraints imposed on environmental locomotional design by wayfinding cognition, but did not tell the designer how to use these constraints. The present chapter develops a set of fifteen design principles that link wayfinding performance to specific features of environmental locomotional design. They suggest to designers ways of analyzing their design situation and provide guidance in using the results of this analysis. In particular, they suggest what design elements may be important and how manipulating them may affect user behavior and performance. For instance, empirical evidence shows that humans often use an egocentric frame of reference based on human anatomy. This might result in design principles that entreat roadway designers to consider whether their users should depend on such frames of reference, and, if so, guide designers to "Think left and think right," that is, to prioritize turns that are orthogonal to the direction of travel.

This chapter develops the principles in two stages. First, it derives a set of twelve principles is derived from the relationships between wayfinding and environmental locomotional design described in Chapter 3. The rationale, grounded in empirical evidence, for each of these is presented along with the principle itself. The application of

---

[xlvi] [241] Reprinted from *Oh, the Thinks You Can Think!*, Dr. Seuss, p.38, ©1975, with permission from Random House Publications (Beginner Books).

each principle to design is then illustrated by its use in a running example aimed at developing a design for everyday file system interaction in traditional desktop environment (the Repeat File Access design). The experience of applying the principles to design suggests that the information needed to satisfy the underlying design constraints implies a certain design process. A brief outline of this process is presented, although formalization and validation of an actual process is beyond the scope of the present work.

The outlined process is then illustrated by its application to a second design example, a design for inter-object navigation in a spatial multiscale environment. This design exercise reveals shortcomings in the initial set of design principles, and suggests three additional principles that seem intuitively obvious, but which are not evident from the empirical evidence. These principles are particularly germane to the design of electronic environments, but also manifest in physical environments. The lack of attention to them in empirical studies suggests that existing psychological knowledge may not be sufficient for design needs, and that developing design knowledge may require the development of new psychological knowledge.

Both design examples—support for everyday file system interaction in a traditional desktop environment and inter-object navigation in a spatial multiscale environment—represent design of electronic user interfaces. The tasks represent commonly performed tasks in their respective environments and were selected specifically to emphasize the need to support wayfinding and to minimize the need for spatial knowledge preservation. The environments were chosen to provide examples of the common and familiar (the desktop environment) and of the novel and poorly understood (spatial multiscale interaction). In both cases, traditional design solutions exist that can be used for comparative purposes.

Note that both designs are based on conjectural user and task analyses, that is, assumptions regarding user needs and behaviors that are based on supposition and have not been validated empirically. In actual design, these assumptions would be obtained from or validated by observational studies and/or formal methods of user or task analysis. Such verification, while highly desirable, requires resources beyond those available for the present work. The present work relies on personal experience—as a user as well as a user interface design professional—combined with evidence from psychological and design literature when possible. Consequently, although application of the principles is expected to aid the usability of the final designs, there is no guarantee that the users at whom the designs are aimed actually exist or that the tasks that the designs support are those that users actually undertake. Nonetheless, the user and task analyses are grounded in both experience and evidence from the literature, so the resulting designs, although not perfect, offer strong starting points for developing realistic designs.

This chapter interleaves development of the third and fourth steps of understanding wayfinding as a problem in environmental locomotional design (Figure 4, p. 14)—deriving implications for design and demonstrating the application to design. The initial set of principles (Figure 26) is the articulation of the implications of the relationships, described in Chapter 3, between wayfinding cognition and environmental locomotional design. The extended set (Figure 74) includes implications that seem evident, but which require further study. The two design examples and the outlined design process demonstrate the application of the implications to design. Interestingly, despite the substantial differences between the tasks and the environments, the two designs yield a single generalized technique, *Predictive Targeted Movement*, for designing and supporting movement in electronic environments. The generic algorithm for this technique is presented, suggesting that the cognitive constraints represented by the principles may be useful not only to the design but also to the development of user interfaces.

Design Example 1: Everyday File System Interaction in a Traditional Desktop Environment

The goal of the file system interaction example is to support users in their day-to-day interaction with files in a hierarchical file system. The assumed interaction environment employs a conventional desktop metaphor with a 2D graphical user interface of windows, icons, menus and pointers (a so-called “WIMP” interface). The example design is based on Windows® conventions, but could readily be adapted to other systems such as the Macintosh™.

The existing design, as represented by Windows® 98[xlvii], offers five standard interfaces for file system interaction. One provides direct access to files and folders that are represented explicitly on the desktop (Figure 21). Two others provide access from the desktop to files and folders that are not represented explicitly. Starting with a folder represented on the desktop, the user may open successive folders in a single window or in successive windows (Figure 22). They may also open the Explorer dialog in which the entire file hierarchy is displayed in one pane and successive folders may be opened in the other (Figure 23). The final two interfaces provide access to files and folders from within an application via use of the standard “File Open” (Figure 24) or “File Save As” (Figure 25) dialogs.

The goal of the present design effort is to explore ways of improving or augmenting existing designs to help users in perform their day to day tasks better, focusing on their interactions with the file system. It is assumed that the basic metaphors of a desktop and files/folders must be retained and that the design must conform to standard design conventions for the environment. It is also assumed that the system is a single user system and that the user-defined file structure, i.e., the contents of the file system and relationships among them, may not be modified. The user is assumed to have “normal” physiology (vision, eye-hand coordination, etc.) as well as “normal” cognitive skills and resources (memory, attention, reasoning, etc.), and to be at least somewhat familiar with computers and the concepts and conventions of the interaction environment.

[xlvii] The industry standard for state-of-the-art when the design work commenced.

Figure 21 Typical user's desktop (under Windows® design).

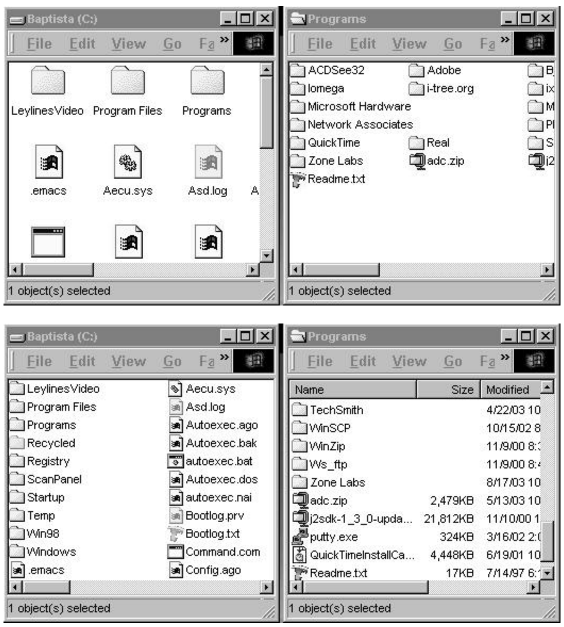


Figure 22 Folder views.

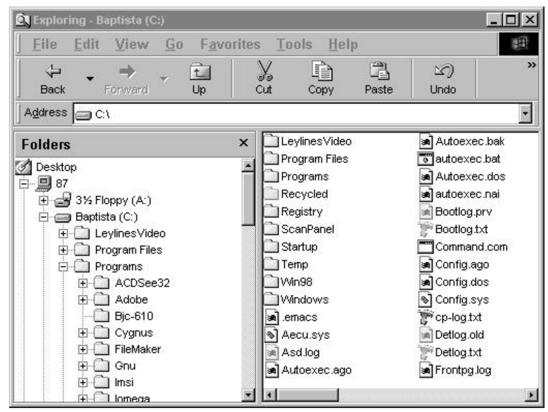


Figure 23 Explorer dialog.

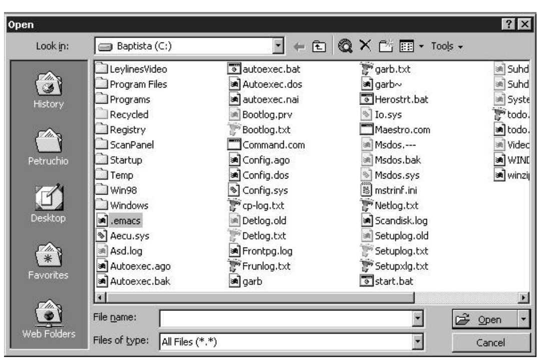


Figure 24 File Open dialog.

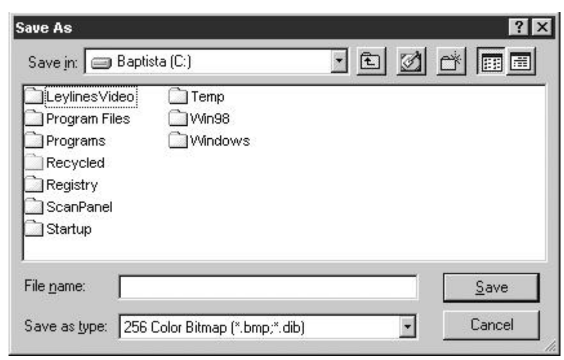


Figure 25 File Save As dialog.

Figure 21 **–** Figure 25 Existing Windows® designs for file system interaction (Windows® 98).

#	Name	Principle	Page
1	**Locations and Paths**	The locations and paths offered by the locomotional structure must be a superset of the destinations and routes in the task-defined structure.	169
2	**Number of Branch Regions**	Increasing the number of branch regions in the locomotional structure is likely to increase wayfinding difficulty, and decreasing the number is likely to decrease difficulty.	175
3	**Complexity of Branch Regions**	The fewer options offered in a branch region, the simpler the wayfinding will be.	176
4	**Task Logic and Organizing Principle**	The more closely the logic of the organizing principle of the locomotional structure corresponds to the logic of the task, the less overhead is introduced by wayfinding cognition.	178
5	**Simplicity of Organizing Principle**	Within the organizing principles made possible by the task, the simpler the principle, the simpler the wayfinding	183
6	**Discontinuities in Plan Organization**	Discontinuities in the plan organization increase the likelihood of wayfinding error.	184
7	**Route Complexity**	The more branch regions along a route, the greater the likelihood of wayfinding error along it.	185
8	**Location of Information Access Regions**	Information access regions must be located within the locomotional structure if they are to figure in wayfinding.	186
9	**Precedence of Information Access Regions**	An information access region entry port must precede or coincide with its associated branch region exit ports, if the information the information region provides is to figure in any wayfinding decisions executed at that branch region.	187
10	**Branch Region Speed**	The less time—per non-viable option—allowed in a branch region, the higher the likelihood of wayfinding error.	188
11	**Information Access Region Speed**	The less time—relative to the amount of information offered—allowed in an information access region, the less likely the information offered is to figure in wayfinding.	189
12	**Steering and Locomotional Structure**	The fewer or less precise steering actions that are required to follow the selected route and to remain within the locomotional structure, the fewer wayfinding errors are likely.	190

Figure 26 Basic design principles derived directly from psychological knowledge

Design Principles

The development of the basic design principles is divided into five sections. The first section contains principles regarding the development of the locomotional structure itself. The second section contains principles aimed at refining the design of information access regions. The third section contains principles concerning the relationship between the locomotional structure and movement. Finally, the fourth section contains principles concerning the relationship between locomotional structure and steering design. The complete set of basic principles is summarized in Figure 26.

The reader is reminded that the term “point” used in the psychological literature was replaced with the term “region” to reflect the more specific understanding necessary to design of concepts such as “branch points” and “information access points” (Chapter 3, *“Point” vs. “Region”: Going from Psychology to Design*, p. 154).

Locomotional Structure

1. Locations and Paths

The locations and paths offered by the locomotional structure must be a superset of the destinations and routes in the task-defined structure.

While not evinced by the empirical evidence, it is axiomatic that, in order for problem-solving and decision-making to yield a viable solution, such a solution must exist. Translated to wayfinding, this means that the destinations and routes necessary to task completion must have corresponding locations and paths in the environment. In other words, the locomotional structure must be a superset of the task-defined structure.

This requirement has one subtle proviso, however. There must be a direct correspondence between destinations and locations, and between routes that are specifically required by the task and paths. Routes that are necessary only because they lead to a required destination need only indirect correspondence to paths. For instance, if the task requires a way to get from destination **A** to destination **C**, there need not be a direct path (i.e., a path with no branch regions) between the two. A path leading through location **B** is sufficient. In contrast, if the task specifically requires an **AC** route, there must be a corresponding **AC** path. This principle necessitates understanding the task sufficiently to identify the task-defined structure.

File System Interaction

Introspection suggests that a user interacts with the file system to achieve one of three purposes: (1) to interact with a specific file or its contents, (2) to place a new file or folder in a specific folder, or (3) to interact with the file system as a whole, e.g., to delete unnecessary files or reorganize the overall structure. The first two purposes are related to the external tasks of searching and finding, as defined in Chapter 2 (*Searching, Finding, Target Acquisition*, p. 63), while the third is more closely related to the external task of browsing (or possibly to other external tasks not identified here). Finding and searching are everyday activities for the majority of users, but although browsing may be a common activity for some users, e.g., system administrators, it is not an everyday activity for most.

In accordance with the standard practice of designing for the common cases first, then exploring ways of accommodating special cases, the less common purpose of file system modification is left for future consideration. Brief consideration of the second purpose—placing a file or folder in the file system—reveals that it may be considered a special case of the first. Assuming that folders and files are not placed randomly in the file system, but are placed relative to existing files and folders, the task of finding the location for a new file or folder is an extension of the task of finding an existing file or folder. That is placing a new file or folder in the system may be considered equivalent to finding where it would be if it were already there. The rest of this example consequently focuses on developing a design for *Repeat File Access*—gaining access to an existing file or folder.

<u>Task-Defined Destinations</u>

Personal experience—both with actual use and from observing users—suggests that the vast majority of files in a file system are not accessed by users directly, but are accessed, if at all, by system or application software. For example, a first installation of

Windows® 98 on a virgin machine left 14,440 files in the file system, before the user had created even one of their own. Some of these were, of course, executables that the user needs to access to start particular applications. However, such executables likely account for a small number of the total files—perhaps up to 50 (based on personal observation) with less than 20 accounting for regular use. This suggests that destinations in the task-defined structure can be described as files that the user has created or accessed directly. Assuming that the user may be working actively with, say, 50 data files, this yields a set of 100 files that are potential targets. A very small number compared to 14,440.

Even within the set of files that the user has created or accessed directly, however, not all are equally likely to be the intended destination at any given time. Evidence exists that past usage of a particular file may provide a predictor for future use. Nardi et al. [15, 190] studied the ways in which people organize and find electronic files within their own file systems. Based on evidence from 15 corporate employees, including managers, graphic artists, programmers, administrative assistants and librarians, they found that information could be classified by duration and frequency of use. *Ephemeral information* is only needed for a short time, and may then be discarded or archived. *Working information* is relevant to the user's current work needs and tends to be accessed frequently. *Archived information* is only indirectly relevant to the user's current work and tends to be accessed infrequently. Archived information was found often to be former working information.

Drucker [65] introduced the term *knowledge work*—"work that applies vision, knowledge and concepts—work that is based on the mind rather than on the hand" [65, p. 120], and later employs the concomitant term *knowledge workers*—"accountants, engineers, social workers, nurses, computer experts of all kinds, teachers, and researchers" [66, p. 112]. Kidd [144] offers a categorization that divides such workers into three categories. *Knowledge workers* (in Kidd's use) are "themselves changed by the information they process" [144, p. 186], *communication workers* change others through information transmission, and *clerical workers* apply information, but are unaffected by it. In effect, in Kidd's terms, a knowledge worker creates knowledge, a communication

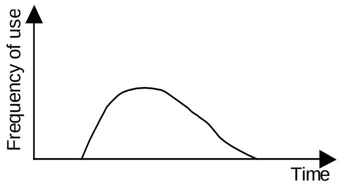


Figure 27 Burst use.

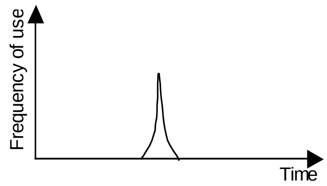


Figure 28 Fleeting use.

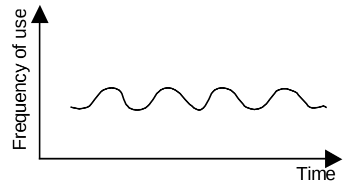


Figure 29 Regular use.

Figure 27 **–** Figure 29 Hypothetical file access patterns.

worker transfers knowledge and a clerical worker applies knowledge.[xlviii] Note that this classification was developed in a corporate context and it is not clear how well it accounts for professionals such as doctors, nurses or architects.

Kidd focuses on analyzing the behavior of knowledge workers (for the remainder of the present work Kidd's usage will be adopted). Like Nardi et al. and Barreau [15], she reports that they exhibit a low dependence on archived information and often report rarely referring to past work. She also reports that they work intensively with a limited amount of working information while it is relevant to their current objectives. Although not reported explicitly, it can be presumed that knowledge workers also engage in communication and clerical activities regularly. None of these studies reports on work patterns for either communication or clerical workers. Consequently, the remainder of this design example will focus on the needs of knowledge workers. The resulting design may, thus, not suit other types of workers.

The behavior patterns reported for knowledge workers suggest three distinct patterns of file usage. In *burst use* (Figure 27), the user uses a file intensively for a period of time and only rarely after that. This pattern characterizes files containing the user's working information, e.g., a report being written. In *fleeting use* (Figure 28), a file is used a few or many times within a short period, then not accessed for a long while. This pattern characterizes files containing ephemeral information or archival information that is temporarily relevant to the current work. In *regular use* (Figure 29), a file is accessed

---

[xlviii] Although all workers engage in all three activities, classification is intended to reflect those that dominate—in theory if not in practice—their efforts.

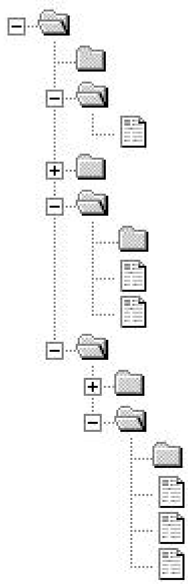


Figure 30 File hierarchy: locomotional structure offered by existing designs.

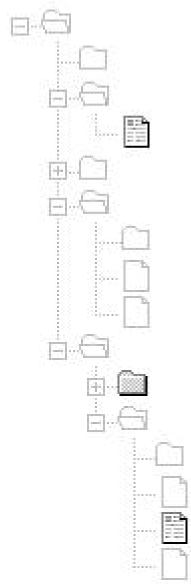


Figure 31 Task-defined destinations.

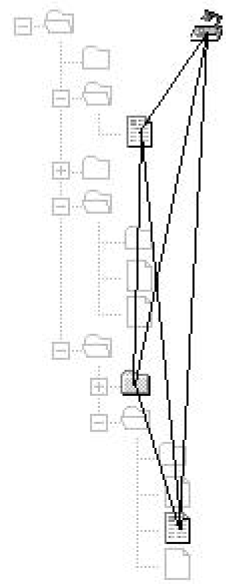


Figure 32 Task-defined structure.

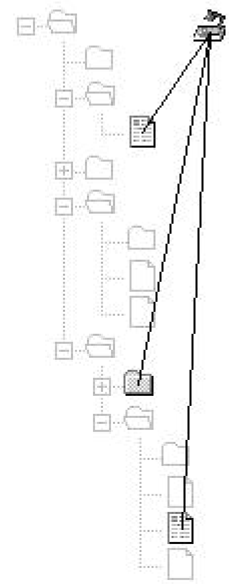


Figure 33 Reduced locomotional structure.

Figure 30 **–** Figure 33 Developing a locomotional structure for Repeated File Access design.

regularly on a continuing basis. This pattern characterizes files containing applications, such as a mail program, an accounting program or an Internet browser, that are used regularly, possibly in the course of communication or clerical activities. In keeping with the findings, it is assumed that the majority of the user’s file accesses are part of a burst or regular use pattern.

Given these assumptions, the likelihood of a file being the user’s intended destination, at any given time, is a function of how recently the user has accessed that file, how often they have accessed it and for how long they used it. This suggests developing a monitoring system that tracks file usage, and calculating the *usage-value* of a given file by applying a formula of the form

$$\frac{duration * frequency}{c * time\ since\ last\ use}$$

where c is some appropriate constant. This usage value reflects the probability of that file being the user's intended destination. Files whose usage value falls above some suitable threshold can then be selected as destinations in the task-defined structure. Figure 30 shows an example file hierarchy, and Figure 31 a possible set of destinations identified in this manner. Although not undertaken here, it is acknowledged that developing a monitoring mechanism and an appropriate formula is itself a complex problem. These difficulties notwithstanding, it is assumed that some reasonable approximation is possible.

Task-Defined Routes

Given the assumption that the user's purpose is to interact with specific file or its contents or, possibly, locate a specific folder, a reasonable goal is to get them to that file or folder as quickly and with as little effort as possible. In other words, it is presumed that this portion of the design does not need to help the user to learn about the structure or content of the file system, or to provide opportunities for serendipitous discovery. This implies that the task does not dictate passing through any particular intermediate locations, and that the task-defined routes lead directly from the current location to the destination. Thus, the routes in the task-defined structure are direct paths from the desktop—the file system entry point—to any destination and from any destination to any other destination (Figure 32).

Task-Defined Structure

Thus, the task-defined structure for repeat file access consists of locations defined by recently and much used (in frequency or duration) files or folders and routes that lead directly between these and between any of them and the desktop (Figure 32). This structure is defined in terms of the way in which files and folders are used, reflecting functional relationships among them. The locomotional structure (Figure 30) offered by the existing Windows® designs (Figure 22 – Figure 25), in contrast, is defined in terms of the way in which files and folders are stored in the file system (Figure 30). This may reflect logical relationships, but, as discussed, does not necessarily reflect functional relationships.

Note that the locomotional structure offered by the existing designs naturally provide opportunities for differentiating locations by the paths by which they were reached. E.g., “I know this is the ‘ToDo’ file for project A rather than project B because I had to go to the ‘Project A’ folder to open it.” The routes in the task-defined structure of the Repeat File Access design only allow such contextual identification if the user consistently and deliberately uses paths leading through the appropriate intermediate locations rather than taking the direct paths offered. The present design assumes that any necessary contextual information can (and should) be provided by the informational design.

2. Number of Branch Regions

Increasing the number of branch regions in the locomotional structure is likely to increase wayfinding difficulty, and decreasing the number is likely to decrease difficulty.

It follows directly from the empirical evidence regarding route complexity (cf. Chapter 3, *Plan Complexity*, p. 135) that the likelihood of wayfinding errors increases as the number of branch regions along a given route increases. It follows from the evidence surrounding plan complexity that wayfinding difficulty is likely to be greater if the locomotional structure has a high number of branch regions (Chapter 3, *Plan Complexity*, p. 135), presumably because this increases the likelihood of any given route having a high number of branch regions.

File System Interaction

In the course of determining the task-defined structure, it was assumed that the design should help users get to their destinations as quickly and with as little effort as possible, without concern for helping them to learn about the structure or content of the file system. This implies that a design goal is to make wayfinding as simple as possible, which, in turn, implies that the number of branch regions should be made as small as possible.

The task-defined structure for the repeat file access task (Figure 32) is a Complete graph that connects all pairs of destinations (including the desktop) in a single step. Each destination is consequently a branch region (assuming that paths are bi-directional). As all routes are single steps, there are no other branch regions. The task-defined structure thus has (N_{used} + 1) branch regions, where N_{used} is the number of files or folders selected as probable destinations.

As the Repeat File Access task-defined structure is a Complete graph, each branch region offers options to all other destinations. Eliminating all but one of the branch regions would result in a structure that provides all routes necessary to task completion, although the paths that compose most routes are then made longer. The desktop branch region is the most stable and, by virtue of the desktop metaphor, is accessible from all locations in the system. It is therefore the natural and obvious choice to retain as a branch region.

This results in the reduced locomotional structure shown in Figure 33, which has only one branch region. The existing designs (Figure 22 – Figure 25), in contrast, have ($N_{folders}$ + 1) branch regions, where $N_{folders}$ is the number of folders in the file system.

3. Complexity of Branch Regions

The fewer options offered in a branch region, the simpler the wayfinding will be.

It follows directly from the empirical evidence regarding route complexity (cf. Chapter 3 *Plan Complexity*, p. 135) that the likelihood of wayfinding errors tends to increase as the number of options in any branch region along a given route increases. It follows from the evidence surrounding plan complexity (Chapter 3 *Plan Complexity*, p. 135) that wayfinding difficulty is likely to be greater if the total number of options offered in branch regions (i.e., the sum of the cardinalities of the sets of options) in the locomotional structure is high, presumably because this increases the likelihood of any particular branch region having a high number of options. Note that the likelihood of wayfinding error decreases as the proportion of *viable* options increases, that is, as a higher proportion of the options available lead to the target destination.

This principle potentially conflicts with the previous principle. Ideally, both the number of branch regions and the number of options in branch regions should be reduced if the goal is to decrease wayfinding difficulty. In practice, a tradeoff must be made between reducing the total number of branch regions and reducing the number of options in individual branch regions. The total number of options in the locomotional structure obviously cannot be reduced to less than the number of destinations. These options can be assigned to a small number of branch regions, each potentially with many options, or they can be distributed over a larger number, each with a small number of options.

Despite claims that certain configurations are optimal, e.g., that fewer branch regions each with more options produces better performance than more branch regions each with fewer options [276], empirical evidence indicates that the trade-off the number of branch regions and the number of branch region options involves factors beyond navigational cognition. For example, Norman and Chin [200], found that the nature of the task was a key factor in determining how options should be distributed across branch regions to produce better performance in menu interaction (cf. Chapter 3, *Task-Defined Structure*, p. 141). van Hoe et al. [274], also studying how task performance might be affected by menu structure, found significant, albeit transient, effects that correlated with the personality characteristics of introversion and neuroticism. These results suggest that further psychological evidence is needed. Therefore, although the present work cannot provide an answer on how to resolve the tradeoff, it at least alerts designers to its existence.

File System Interaction

The Repeat File Access locomotional structure developed thus far (Figure 33) has a single branch region with options to all destinations. If the earlier estimate of up to 100 destinations is realistic, this one branch region is probably overly complex. The set of destinations cannot be reduced further, so the only possibility is to increase the number of branch regions and distribute the options among them. The existing desktop metaphor does not allow for the introduction of additional top-level locations, e.g., multiple desktops[xlix], so it is necessary to introduce intermediate branch regions that, in effect, subdivide the desktop branch region. This requires finding a meaningful way of grouping

---

[xlix] E.g., a design such as that offered by the “Rooms” windowing environment [110].

destinations, and will be discussed when *Principle 4 Task Logic and Organizing Principle* is applied to the design.

4. Task Logic and Organizing Principle

The more closely the logic of the organizing principle of the locomotional structure corresponds to the logic of the task, the less overhead is introduced by wayfinding cognition.

The psychological evidence regarding the relationship between task logic and the organizing principle of the locomotional structure (Chapter 3, *Task Logic*, p. 144) suggests that the more closely the two correspond to each other, the less overhead is introduced by wayfinding. Correspondence can entail matching semantic logic to spatial organization, for example, presenting a list of names as a linear sequence alphabetized by first name. It can also entail matching spatial logic to spatial organization, for example, presenting a list of names as a seating chart. Alternatively, it can entail matching temporal logic to either spatial or temporal organization, for example, presenting the list of names in the order in which they are needed or presenting them one by one in the order needed. Which task logic or logics should predominate must be determined by the designer in accordance with the needs of the immediate design situation.

File System Interaction

Thus far, no organizing principle for the Repeat File Access locomotional structure has been defined: the locomotional structure consists of a single branch region with options to all other locations (Figure 33). Application of Principle 3 *Complexity of Branch Regions* suggested introducing a set of intermediate branch regions in order to reduce the number of options in any given branch region, but did not suggest a means of categorizing and organizing options into multiple branch regions. While no information regarding the logic of superordinate task(s) is available, the behavioral analyses described when identifying task-defined destinations (*Task-Defined Destinations* p. 170) suggest a simple logic to the repeat file access task.

The behaviors described outline a pattern of intensive and extensive interaction with a small amount of information, occasionally interrupted by brief accesses to other information. This activity is interspersed with regular tasks that are themselves unchanging, but that involve changing information, such as reading email. These behaviors were reflected in the burst, fleeting and regular use file usage patterns described. The patterns can thus be presumed to reflect some underlying logic of the user's task, and to provide a simple principle for grouping branch region options and creating intermediate branch regions.

Dividing destinations into three groups based on usage patterns, however, immediately presents two practical difficulties. First, detecting actual usage patterns requires far more complex analysis of the usage data than the simple formula used for determining a file's usage value. Second, even given the ability to distinguish usage patterns, it is impossible to discriminate between fleeting use and the beginnings of a burst pattern. However, it is likely that fleeting use reflects part of the knowledge development task, so grouping burst and fleeting use files is likely to be consonant with the underlying task logic.

Overcoming the second difficulty by grouping burst and fleeting use files together suggests a possible means of circumventing the first. Although it is assumed that a mechanism for detecting usage patterns can be developed, file types may offer a simple, and possibly sufficient, heuristic for determining probable usage patterns. Note that regular use files were assumed to be associated with regularly occurring *tasks*, whereas burst use files were associated with working and ephemeral *information*, respectively. This leads to the presumption that regular use files will most likely be application files and burst/fleeting use files will be data files.

Grouping branch region options by file type raises the question of how to treat file folders. Although speculative, it is supposed here that folders are used in two ways. First, they serve as containers from which information may be retrieved and into which it may be stored. Second, they serve as collections of related information. In the former case, the focus is on the *container,* whereas the focus of the latter is on the *context it represents*.

In the first case, the user's need to interact with the folder stems from the need to access a file within it or to save a file to it. The Repeat File Access design handles this first need by providing direct access to the file, circumventing the need to access the folder (note that first access to a file is not addressed here, although it must be addressed in a design intended to cover all contingencies). The need to place a file in any folder of the file system corresponds to the task of modifying the file system, which is also not addressed here.

In the case of the folder serving as an information context, the user's need to interact with the folder stems from the need to access the context it represents. That is, the user may open the folder in order to interact with multiple files within it, to open a file that is related to one that is already open or to save an already open file within a particular context. In the first case, the folder is acting like a composite file and its usage is likely to mimic that of any simple file. This argues that, in lieu of categorizing the actual usage patterns of folders, they could be grouped with the regular use files, with the burst/fleeting use files or they could form a group of their own. The importance of working information to the knowledge worker argues for one of the latter choices. In order to limit the size of the burst/fleeting use group, the Repeat File Access design somewhat arbitrarily opts for making folders a separate group.

When the user interacts with the folder context in order to open or save a file that belongs there, the user is working from within an application. This indicates that folder destinations must be accessible from the standard "File Open" (Figure 24) and "File Save As" (Figure 25) dialogs. Note however, that the context the user is seeking is likely to be either the context of the already open file or the context of a previously opened file. This suggests that folders containing files that have been selected as burst or fleeting use destinations should themselves be considered potential destinations. In other words, in addition to folders that the user has accessed directly, the folder group should include folders that contain data files that are in the burst/fleeting use (data) file group.

The revised locomotional structure thus has four branch regions (Figure 34): the desktop branch region and three intermediate branch regions leading, respectively, to Regular use destinations (applications), Burst/fleeting use destinations (data files) and Folder destinations. (Note that the Folder branch region has an added option, compared to the previous locomotional structure Figure 33, that leads to the containing Folder of the data file destination.)

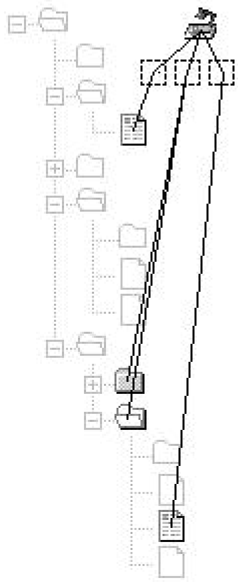


Figure 34 caption:

Figure 34 Revised locomotional structure containing three intermediate branch regions for Repeated File Access design.

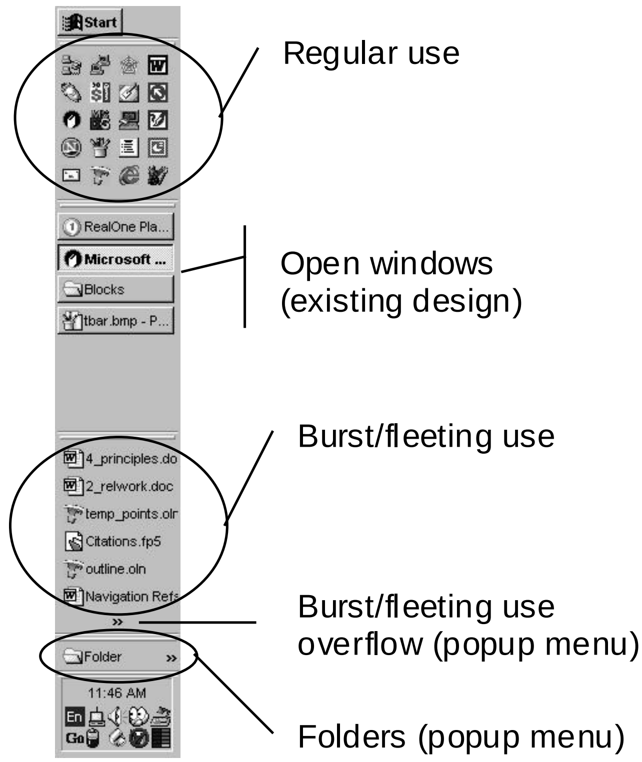


Figure 35 Mockup of modified taskbar containing three intermediate branch regions for Repeated File Access design.

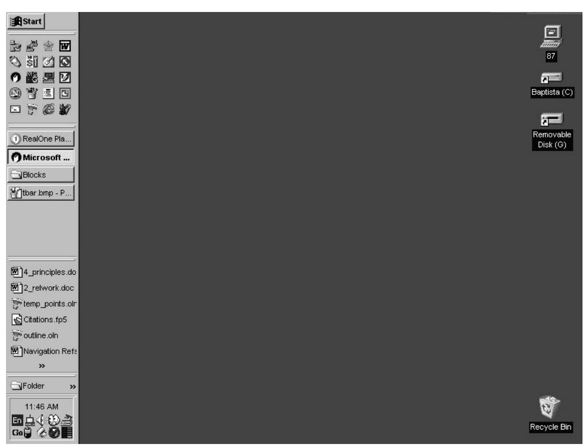


Figure 36 Mockup of desktop showing modified task bar on left for Repeated File Access design.

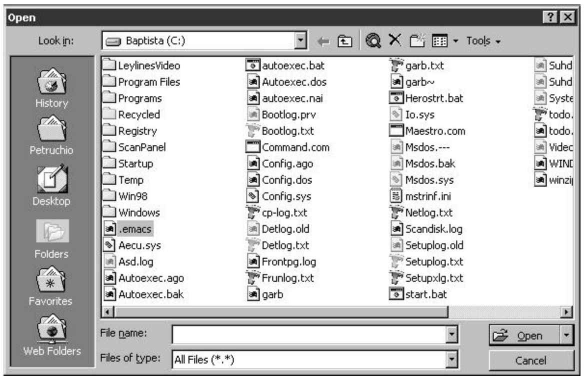


Figure 37 Mockup of File Open dialog for Repeated File Access design.

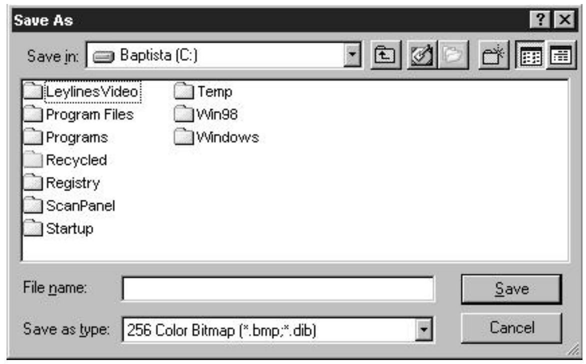


Figure 38 Mockup of File Save As dialog for Repeated File Access design.

Figure 35 shows a mockup of how the intermediate branch regions might be incorporated into the existing design. As these must be accessed directly from the desktop, they are incorporated into the existing Taskbar[l]. The Regular use destinations appear as a block of icons. It is assumed that applications will appear uniquely, and that regularly used files can be differentiated, if necessary, using ToolTips[li] to show the filename. Burst/fleeting use destinations appear as a list of filenames, of which the first few are shown and the remainder appear on a popup menu. These might be ordered according to their usage value (computed when destinations are selected), i.e., most often, recently or longest used files first, or the user may want a fixed ordering, e.g., alphabetical. Finally, Folder destinations appear as a popup menu, and an access button is added to the existing “File Open” (Figure 37) and “File Save As” dialogs (Figure 38).

Note that the Repeat File Access design removes the so-called “finding” (file access) function from the desktop surface itself (Figure 36). This leaves the desktop area free to serve as a workspace where actively used materials are placed, and may reduce the clutter often found on users’ desktops (Figure 21). Reducing the clutter allows the

---

[l] A region of the desktop that is dedicated to act as a menu. It contains, among other things, buttons to access open windows or applications. It may be configured to be open continuously or act as a popup menu.

[li] Brief textual information that pops up when the mouse is over an item.

"reminding" function—leaving objects on the surface as memory aids—of the surface to become more prominent.

The design also automatically addresses a deficiency in the Windows® design. While the user can access open windows from the Taskbar (Figure 35), there is no corresponding means of accessing open folders (i.e., folders that are open on the desktop) from within applications. It is not uncommon to have the containing folder of the currently open files also open on the desktop, and to want to open files from or save them to this folder. In the existing design, it is generally necessary to traverse the file hierarchy to find the appropriate folder. In the proposed design, open folders are added to the Folders branch region automatically, and are therefore readily be accessible from within applications.

5. Simplicity of Organizing Principle

Within the organizing principles made possible by the task, the simpler the principle, the simpler the wayfinding.

It follows directly from the evidence surrounding plan organization (Chapter 3, *Plan Organization*, p. 137) that the complexity of the organizing principle tends to be directly related to wayfinding complexity. That is, the simpler the principle, the simpler the wayfinding. Note that "complexity" here is relative to human understanding and application of the organizing principle. This may be related to computational or descriptive complexity, but is not synonymous. For instance, humans process visual information easily whereas computers do not. E.g., "visual emphasis" in the composition of paintings "focuses the viewer's attention … by accentuating certain shapes, intensifying value or color, featuring directional lines, or strategically placing the objects and images" [115]. This results in a visual organization that humans can readily understand and use, but which may be difficult to describe or calculate computationally.

File System Interaction

The proposed organizing principle for the Repeat File Access based on a combination of file type and past usage. Discerning file type is simple both computationally and, it is presumed, for human comprehension. Tracking past usage, however, relies on properties of human memory that may not easily be modeled computationally. Computationally, it may be difficult to develop a system to monitor actual file usage and determine a precise usage value formula. The human user, in contrast, is likely to have a reasonably accurate sense of which files they have used and how extensively they were used without consciously seeking to acquire such information. The proposed organizing principle is thus deemed sufficiently simple.

Nonetheless, it is expected that the user may wish to override system assignments for a specific file, both for destination selection and for branch region assignment. For example, the user may wish to include certain files or folders in a particular branch region permanently, regardless of usage, or they may wish a particular data file to be assigned to the Regular use branch region whenever it is "active."

6. Discontinuities in Plan Organization

Discontinuities in the plan organization increase the likelihood of wayfinding error.

The evidence surrounding plan organization (Chapter 3, *Plan Organization and Behavior*, p. 139) suggests that discontinuities in the plan organization increase the likelihood of wayfinding errors. Discontinuities may be introduced by the juxtaposition of different organizing principles, e.g., building interiors arranged according to compass directions while the external road system is arranged in accordance with environmental features, or some books in a library being arranged by topic while others are arranged by author. Discontinuities may also result from the embedding of an organizing principle in an environment, for instance, where intermediate parts of a North-South road actually face East-West. Finally, temporal discontinuities may arise if the contents of the locomotional structure are subject to change, for instance, when new roads are built.

File System Interaction

Only one organizational principle is used in the Repeat File Access design so no discontinuities are introduced by employing multiple organizational principles. However, the proposed design itself introduces a different organizing principle from that used in the conventional design (the hierarchical file structure). Thus, if it is to be embedded in the conventional desktop environment, and the existing designs for file system interaction (Figure 22 – Figure 23) used for interaction with the filesystem as a whole, e.g., for cleanup or restructuring, discontinuities will be created. Evaluating the extent of the difficulties of integrating the two designs and means of addressing the resulting discontinuities is beyond the scope of the present work.

Although no discontinuities are introduced that are related to the organizing principle, the dynamic nature of destination selection may introduce temporal discontinuities in branch region contents. If the usage value metric is used by the informational design to organize the presentation of branch region options, this presentation may change frequently. How much difficulty this causes depends on the behavior and preferences of individual users. However, it is expected that it would be desirable to allow users to select between organizing principles for individual branch regions, for instance, by usage or alphabetically by filename.

7. Route Complexity

The more branch regions along a route, the greater the likelihood of wayfinding error along it.

The psychological evidence surrounding plan complexity (Chapter 3, *Plan Complexity*, p. 135) showed that the number of branch regions on a route directly affects wayfinding difficulty along that route. While manipulation of the overall number of branch regions in the locomotional structure affects the number of branch regions any given route is likely to have, it may be desirable for the designer to manipulate individual routes, for example, eliminating branch regions from frequently used routes and shifting less frequently used options to less frequently used routes.

File System Interaction

There are two types of routes in the locomotional structure of the Repeat File Access design: routes leading from the desktop to a destination, and routes leading from one destination to another. Routes leading from the desktop to a destination comprise only the appropriate intermediate branch region, and so are quite simple. These routes are made particularly simple by the incorporation of the branch regions into the existing Taskbar; in many cases, getting to the branch region from the desktop only requires moving the mouse. In the remaining cases, the user will also have to press a mouse button to activate a popup menu.

The second type of route, leading between destinations, requires the user to go to the desktop, and then follow the first type of route. Although these routes conceptually have two branch regions (the desktop and the appropriate intermediate branch region), in practice they only require the same behaviors of the user as routes originating on the desktop. This is due to the behavior of the Taskbar, which is designed to be accessible directly from both the desktop and from within applications. Thus, all routes in the Repeat File Access design locomotional structure are simple.

Information Access Regions

8. Location of Information Access Regions

Information access regions must be located within the locomotional structure if they are to figure in wayfinding.

If an information access region is to provide access to information, it is necessary for the wayfinder to be able to get to it. Thus, although information regions may be positioned anywhere, information access regions must be positioned somewhere within the locomotional structure. Further, an information access region can only occur where the perceptual and locomotional structures intersect, for instance, where lines of sight cross paths or a path crosses a region within which the wayfinder can touch some object. Thus, the positioning of information access regions results from a combination of locomotional, informational and perceptual design.

File System Interaction

WIMP interfaces, such as that underlying the file system interaction design, are rooted in a tradition called “direct manipulation” [244]. This tradition dictates that any object the user is to manipulate must have a continuous perceptible representation, and that the user interacts with this representation in order to manipulate the object. It also dictates that, if a representation of an object is available, it should be manipulable. (Direct manipulation interfaces are typically contrasted to command line interfaces where objects are manipulated by typing text.)

In WIMP interfaces, information is provided visually and can only be provided in open windows. (The desktop is a special window that is always open.) A window is thus simultaneously an information region and an information access region. As the visual representation is also the user's means of interacting with the object, it can be assumed that any branch regions or branch region options shown in a window can be accessed or selected, i.e., if you can see it, you can get there. Windows are thus also branch regions, and are located within the locomotional structure. As all information access regions are windows and all windows are located within the locomotional structure, all information access regions are located within the locomotional structure in any WIMP design.

Note that, windows have extent only in the horizontal and vertical dimension, but not in the direction of movement. Branch and information access regions are thus not only spatially coincident, but their entry and exit ports also coincide and correspond to an entire window. In the standard interaction wherein movement stops at windows (i.e., it is not possible to "fly" through them), the temporal distance between entry and exit ports is conceptually infinite, but, in practice, controlled by the user.

9. Precedence of Information Access Regions

An information access region entry port must precede or coincide with its associated branch region exit ports, if the information the information region provides is to figure in any wayfinding decisions executed at that branch region.

The evidence surrounding general problem-solving and decision-making clearly show that information must be obtained prior to developing or updating the mental representation, and that option generation and selection depend on the resulting mental representation (cf. Chapter 3, *General Problem-Solving and Decision-Making*, p. 95). This implies that the information must be available before or at the time the decision is made. As the decision must be made before it can be executed, but need not be made earlier, this implies that the latest the information can be presented and still be useful is the time of decision execution. In other words, if the information made available by an information access region is to be used in selecting a particular option in a branch region, the information access region entry port must precede or coincide with the branch region exit port. Information obtained at succeeding information access regions may be used to detect and correct errors and may serve to confirm the decision (e.g., so-called “reassurance signage”), but cannot figure in the decision itself.

File System Interaction

As has already been noted, branch region exit ports and information region entry ports always coincide in a standard WIMP file system interface. While this guarantees that information will be available when a decision is to be made, it does not guarantee that the available information will be either necessary or sufficient for making a “good” decision. However, determining requirements for the informational content of information regions is a matter of informational design, and so is not treated here.

Relationship between Movement and Locomotional Structure

10. Branch Region Speed

The less time—per non-viable option—allowed in a branch region, the higher the likelihood of wayfinding error.

If a comparative model of problem-solving and decision-making (cf. Chapter 3, *General Problem-Solving and Decision-Making*, p. 95) is used—i.e., all options must be considered—the time needed to select an option is proportional to the number of options. If a singular generation and evaluation model is used—i.e., options are considered sequentially until one that is acceptable is found—the time needed to select an option depends on the number of unacceptable options considered before a selection is made. Both models suggest that the likelihood of wayfinding error is likely to increase if the wayfinder has insufficient time to consider all options. If the branch region has multiple viable options, the time required to select a viable option (with certainty) is related to the number of non-viable options (cf. Principle 3 *Complexity of Branch* Regions, p. 176). Thus, speed of movement can be adjusted according to the proportion of viable options.

File System Interaction

In the Repeat File Access design, movement stops at all branch regions. Wayfinders are thus allowed infinite time to make their selection. Note, however, that the application of this principle extends the possibility of pausing (rather than stopping) movement at branch regions that have only a single option. That is, if the user does not indicate otherwise, the single option is selected automatically, potentially reducing the time spent in the branch region.

11. Information Access Region Speed

The less time—relative to the amount of information offered—allowed in an information access region, the less likely the information offered is to figure in wayfinding.

The development of a mental representation depends on information gathered from the environment (Chapter 3, *Mental Representation*, p. 119). This implies that the amount of time spent in an information access region must be sufficient for the wayfinder to perceive and process the available information offered if it is to be incorporated in the mental representation, and, subsequently, figure in wayfinding problem-solving and decision-making. If the information is complex, either perceptually or conceptually, the time required is likely to be proportional to the amount of information offered.

Note, however, that informational and perceptual designs are subject to principles of Gestalt psychology [149]. These suggest that presentation can cause certain elements of the information presented to become salient, for instance, a red dot in a field of blue dots is likely to be perceived immediately (the so-called “pop-out effect”). If only perceptually salient information is relevant to the wayfinding task, the time required is proportional only to the amount of salient information (assuming that the wayfinder is able to recognize it as the relevant information). Perceptual modality and information representation may also affect the time required for perception and assimilation.

File System Interaction

As discussed during the consideration of branch region speed (p. 189), all windows are information access regions and movement stops at each window. The wayfinder is thus allowed infinite time to perceive and absorb the information presented in the Repeat File Access design.

Relationship between Steering and Locomotional Structure

12. Steering and Locomotional Structure

The fewer or less precise steering actions that are required to follow the selected route and to remain within the locomotional structure, the fewer wayfinding errors are likely.

The evidence surrounding the relationship between steering design and locomotional structure (Chapter 3, *Relationship between Steering Design and Locomotional Structure*, p. 151) suggests that the less wayfinders have to do in order to follow the selected route, the less likely they are to deviate from it. Wayfinders may deviate from a route and remain within the locomotional structure, or they may depart from the locomotional structure altogether.

Within the locomotional structure, the steering design controls not only whether incorrect options may be selected, but also how many actions are necessary to move within the locomotional structure. For example, inertial steering systems, which keep drivers from constantly having to make minor corrections to keep a car moving straight ahead, and cruise control, which eliminates the need for the driver to maintain pressure on the accelerator, have simplified the task of keeping a car moving forward greatly. However, steering a car, which can move freely within the boundaries of the locomotional structure, still requires more actions than steering a train, which is constrained to move toward a particular location in the locomotional structure.

By definition, movement is not possible outside a locomotional structure. However, multiple locomotional structures may overlap in such a way that it is possible to transfer from one to another unintentionally. In the physical world, this is generally known as an "accident," e.g., when the car goes off the road or the train goes off the track.

File System Interaction

In a pure WIMP interface, i.e., one that does not allow typed-in commands, movement is only possible from window to window[lii] and within a window. Thus, while it is possible to leave the usage-based structure of the Repeated File Access design for another locomotional structure, it is not possible to go to an incompatible locomotional structure. Leaving the usage-based structure is possible at folder locations where the usage-based structure intersects any locomotional structures that are based on the file system hierarchy—e.g., by opening a folder from the Folders group. If the user chooses to leave the usage-based structure by selecting a previously unused file or folder—e.g., by opening a previously unused folder from within a folder window—the usage-based locomotional structure is, of course, extended to include that file or folder. (Note that, if such movement was unintentional and is not repeated, the usage is fleeting and will rapidly drop from the usage-based locomotional structure. Transitions between locomotional structures are thus intentional, or, at least, cause no lasting harm.

The steering design—clicking on the representation of a destination to go there—offers no degrees of freedom of movement within path boundaries. Thus, no further action is required once a selection has been made. The design attempts to prevent users from making incorrect selections by not offering them as options rather than by preventing them from being selected.

Thus, the steering design requires few actions to remain within the locomotional structure and does not require precise actions while moving.

[lii] Note that a menu is a form of window.

Design Summary: Everyday File System Interaction

In summary, the Repeat File Access design relies on standard WIMP design elements and interaction. The design comprises two subsystems: a monitor that tracks file access and usage, and a user interface that uses these data to provide rapid access to certain files and folders. The monitor gathers data about how often and how long files that were opened at the explicit request of the user are used. Development of such a monitor poses significant challenges, but is not addressed here.

The user interface uses these data to compute a usage-value for these files and folders based on how recently, frequently, extensively and regularly they have been used. Development of an exact formula for calculating usage-values is acknowledged a difficult problem, but is not addressed here. Files and folders that have a high usage-value are then divided into three groups based on file type: Applications, Folders and Data Files. All three groups are made accessible directly from the desktop, e.g., by including them on the existing Taskbar (Figure 35, Figure 36). Access to the Folder group is also provided by modifying the existing “File Open” (Figure 37) and “File Save As” (Figure 38) dialogs. The user uses standard “click to open” to access the files or folders displayed. Although the three groups are permanent, their contents vary dynamically. It may be desirable to provide user preference settings for their display, and to allow users to override system selection and group assignment of files and folders on a file-by-file basis. The design is consistent with the 12 design principles derived from the psychological evidence.

This design represents a theoretical treatment of the underlying design problem, and explicitly does not address all aspects of file system interaction or all aspects of design. Specifically, it subdivides file system interaction into three subtasks and addresses only one of them, that of repeated file access. It does not address the cases of initially accessing a file or that of browsing and modifying the file system as a whole. It also does not consider opportunities for improving informational or steering design, but relies on existing mechanisms for providing these.

Although the Repeat File Access design does not consider the remaining two subtasks, it complements existing designs that support these tasks. The present design

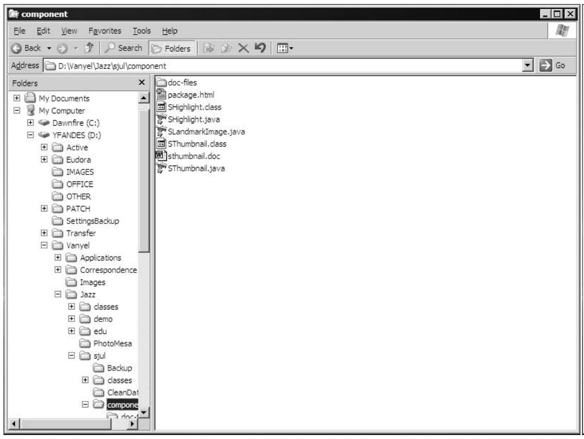


Figure 39 File system interaction with existing Explorer dialog.

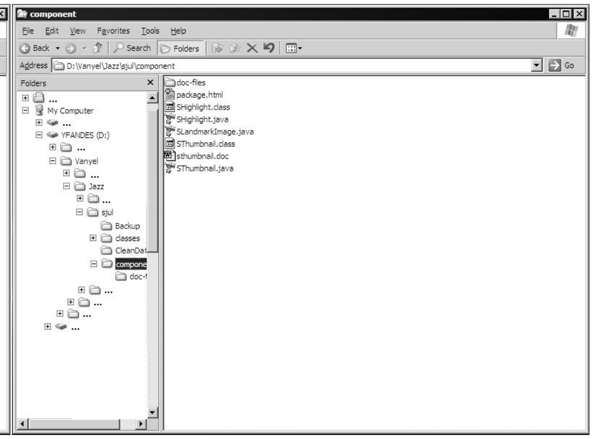


Figure 40 File system interaction with modified Explorer dialog.

effort has, in essence, yielded a "desktop manager" mechanism that helps users to organize and interact with their working materials. It should not be regarded as an alternative design for all file system interaction. The proposed design integrates naturally with the existing designs through the Folders group. This group is accessible from the existing mechanisms for opening and saving files (File Open and Save As dialogs). It provides access to the existing mechanism for interacting with the entire file system (individual file folders) and, through this, to the existing mechanism for interacting with the file system as a whole (the Windows® Explorer). Thus, although the present effort has not considered the needs of the two other subtasks, it does not preclude their execution.

(Note that the conjectural task analysis immediately suggests an alternative for interaction with the Windows® Explorer. This analysis led to the assumption that many file accesses exhibit locality of reference, that is, that the destination file is likely to be in the vicinity of a previously opened file—either in the same folder or in a "nearby" folder—resulting in the automatic addition of containing folders of open files to the Folders group (p. 180). If this assumption holds for a significant proportion of initial file accesses as well, a design that progressively exposes more of the file system at the user's request might be advantageous.

For instance, in the existing Windows® design, if the user opens the Explorer, the entire file hierarchy is displayed with their current location highlighted (Figure 39).

Figure 40 shows a crude design that elides folders that are not in the immediate portion of the hierarchy. The user can then open neighboring folders as required. Better techniques exist for selecting and displaying an appropriate context; the mockup provided here is merely intended to convey the feel of minimizing the visual representation of “other” portions of the file hierarchy. An actual design would, of course, provide for more sophisticated interaction, including a one-step revealing of the entire hierarchy, i.e., display the view in Figure 39.)

While the Repeat File Access design may seem novel, it does not, in fact introduce fundamentally new interaction techniques. Rather it elaborates on the concept of a history list and combines it with the concept of bookmarks. Most existing uses of history mechanisms are simple lists that rely only on recency of use. The proposed design introduces a sophisticated history metric that considers duration and frequency of use as well as recency. This prevents, for instance, the file containing the actual report being written from being omitted from the list because of a search for the right illustration to include. The design also differs from most current history mechanisms in that it does not present the selected files as a single list, but uses an additional dimension—namely file type—to subdivide the list. This allows sublists to be represented differently, potentially taking advantage of different visual representations. Finally, the design differs in that it allows users to override system selections, in effect, allowing users to combine a history list and a bookmark list.

Implications for Design Process

The order in which the design principles were presented was not random, but was partially dictated by the demands of developing an actual design. This suggests that the process of satisfying the constraints underlying the principles prescribes a certain process for the development of design. A brief outline of this process is offered here. The outlined process is based on the experience of developing the principles and the Repeated File Access design, and is intended to be suggestive rather than definitive. The outline is offered without rationale or explanation. It foreshadows how the application of the principles to design might be formalized eventually.

The process offers five steps for the problem analysis and design generation phases of designing environmental locomotional design:

1. Identify navigational design goals using appropriate requirements analysis methods.
2. Identify the task-defined structure using appropriate task analysis methods.
    a. Determine how “destination” and “route” are defined in terms of the task.
    b. Determine what destinations and routes are necessary to task completion.
    c. Add destinations or routes necessitated by non-wayfinding design goals (e.g., for marketing or security purposes).
3. Generate one or more initial designs.
    a. Generate an initial locomotional structure by mapping destinations and routes onto locations and paths defined by pre-existing design (if any).
    b. Define a locomotional mechanism that produces the initial locomotional structure and is consistent with the task-defined structure.
4. Refine necessary and sufficient design by application of design principles, iterating between principles to resolve tradeoffs as necessary.
5. If design goals call for wayfinding to be more difficult than necessary simply to meet wayfinding needs (e.g., to increase the challenges offered by a game or to increase learning outcome): Modify the design to increase wayfinding complexity by application of design principles.

Note that the process suggested by Passini [213] (cf. Chapter2, *Romedi Passini: Wayfinding in Architecture*, p. 87) for developing informational design naturally follows the final step (4 or 5 depending on design requirements) of the process outlined here.

Design Example 2: Inter-Object Navigation in Spatial Multiscale

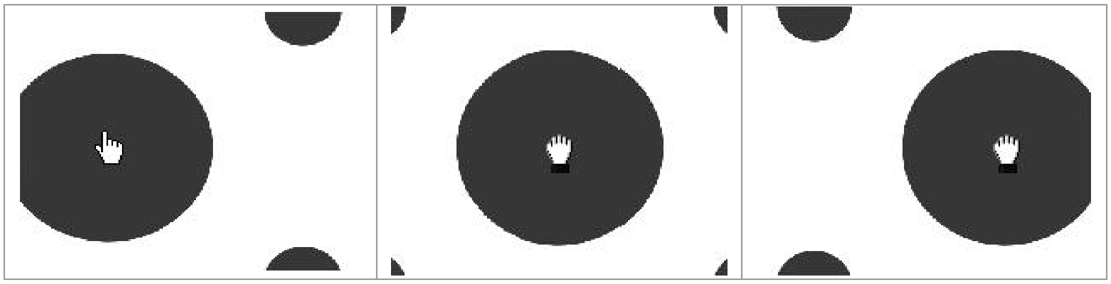
In order to verify the generality of the principles and to illustrate their application to design further, a second design example is developed. The first example—file system navigation in a conventional desktop environment—sought to support a specific task in a well-known environment. The second example—inter-object navigation in spatial multiscale environment—seeks to explore ways of providing general navigational support in a novel environment.

A multiscale environment is one in which information exists at multiple levels of detail. For example, in the physical world, objects exist at scales ranging from galactic to atomic. In spatial multiscale environments, different levels of detail coexist spatially, as in the physical world. A hierarchical file system is an example of a non-spatial multiscale environment. A directory or folder represents a collection of files and folders regarded at an aggregate level of detail so the environment is multiscale. However, a directory or folder exists in a different location from its contents—for instance, the location of the folder icon representing the folder is spatially distinct from the window representing the contents—so it is non-spatial.

The example is developed by following the process outlined in the previous section, and serves to illustrate that process. Two different designs emerge. One of these, the *Voronoi-based design*, is more general but less conventional, while the other, the *geometry-based design*, is less general but more consistent with conventional design thinking. The latter is consistent with the twelve design principles. The former, however, draws on design intuition and appears to contravene some of the principles. As the intuitions are borne out by empirical studies (reported in Chapter 5), the apparent contradictions will be explored in some detail and three additional design principles will be hypothesized to account for them.

Jazz: A Spatial Multiscale Interaction Environment

Jazz [22, 116] is an application framework for designing and building electronic spatial multiscale tools and environments. Like its predecessors Pad [218] and Pad++ [20, 21], the Jazz interaction environment employs a metaphor of a conceptually infinite two-dimensional surface that can be viewed at an infinite range of magnifications or scales. Both planar and scale dimensions are conceptually continuous.



The user clicks on the surface to pan.

When the mouse is dragged (here to the right), the surface moves a corresponding distance in the indicated direction relative to the viewing window.

Figure 41 Panning in Jazz.

The Jazz framework defines a universal *space-scale* coordinate system that allows any point to be specified uniquely in terms of its position on the surface and a scale coordinate. This coordinate system used to describe a variety of entities such as the position and extent of objects. Objects have position and extent on the surface, and can alter their visual representation depending on the magnification (scale) of the view, including changing their visibility. For example, it is common practice to make objects invisible when the amount of detail is deemed too small to be useful (Figure 43). Views of the surface may be specified by the planar coordinates of the point that is at the center of the view and the magnification of the view [82]. The standard movement model allows view movement by panning (changing planar but not scale coordinates, Figure 41) and by zooming (changing the scale coordinate of the view, but not its planar coordinates, Figure 42).

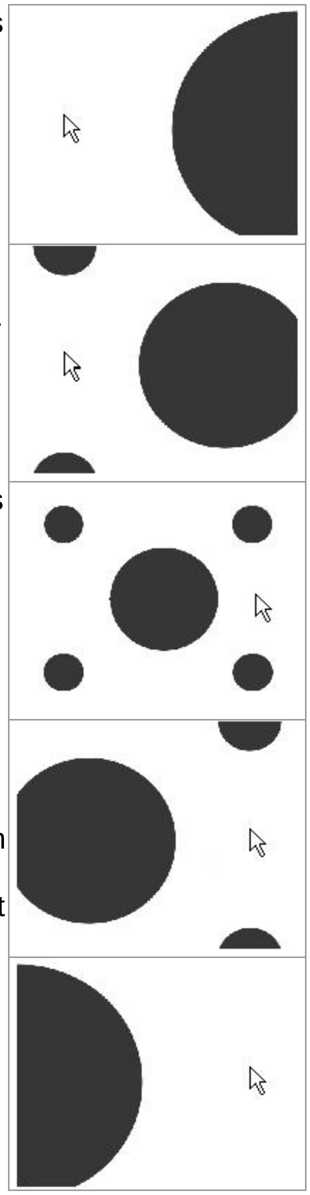
Traditionally, locomotion is *geometry-based*, i.e., defined to relative to the geometry of space-scale. When zooming, the point under the mouse is the center of the zoom, i.e., that point stays in the same position in the viewing window while the view magnification changes (Figure 42). When panning, all points on the surface move uniformly relative to the view window, but the view magnification is unchanged (Figure 41). Some steering designs allow composite pan and zoom movement.

When the user clicks to zoom out, the view of the surface contracts around the point under the mouse.

Decreasing the magnification of the view may bring other objects into view.

When the user clicks to zoom in, the view of the surface expands around the point under the mouse.

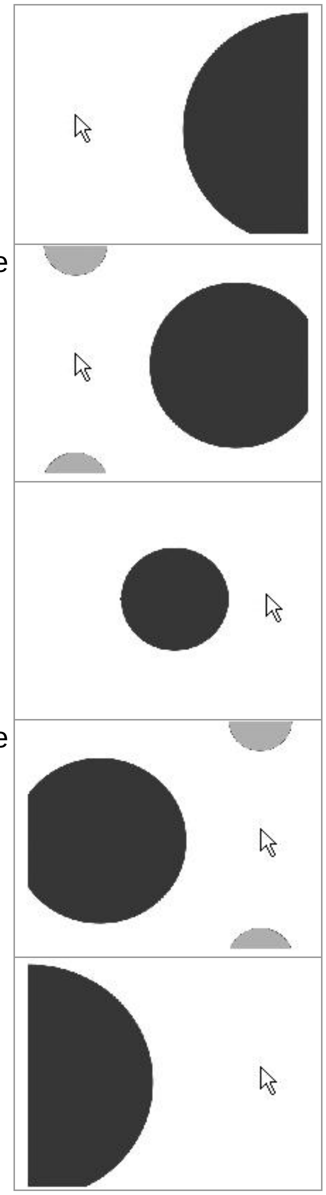
Note that different portions of the surface will be viewed if the zoom-in center differs from the original zoom-out center.



As the scale of the view nears the minscale[liii] of an object, that object begins to fade.

If the scale of the view is smaller than the minscale of an object, that object is not visible.

As the scale of the view passes the minscale of an object, that object begins to become visible.



Cursors indicate respective zoom centers.

Figure 42 Zoom-out followed by zoom-in using conventional geometry-based locomotional structure.

Figure 43 Same zoom sequence with some objects fading gradually.

[liii] The minimum magnification at which the object can be seen (see *APPENDIX C Understanding Space-Scale Diagrams**, p. 299 for further explanation).

Navigational Design Goals

The design goal of exploring “basic navigational support” defines neither the task to be supported nor the superordinate task that it serves. The design requirements only indicate that the task takes place in the Jazz environment. However, it can safely be assumed that the task entails one of three navigational activities: (1) locating an existing object in order to interact with it, (2) placing a new object on the surface or moving an existing object, or (3) modifying the layout of objects on the surface. As in the file system task, it can be argued that, as object placement is not random, the second purpose can be viewed as a special case of the first (*File System Interaction*, p. 170). In other words, the first and second activities are examples of finding or searching tasks.

The third purpose is more closely related to a browsing task. Because of the nature of spatial multiscale, in which objects may have varying locations and extents both on the surface and in scale, it is impossible, in most layouts, to reach a view where all objects can be seen at once. Browsing or modifying the layout thus requires a special editing tool that allows the layout of objects in both planar and scale dimensions to be viewed and edited. Such a tool has been suggested by Furnas and Zhang [83][liv].

The design developed here, consequently, focuses on the first task—inter-object navigation. It is assumed that the system is a single-user system and that the user is familiar with the layout of the objects on the surface. In other words, the design is not intended to help a user explore the contents of the environment, but is intended to help them move to objects as quickly and efficiently as possible. It is also assumed that the layout, appearance or behavior of objects on the surface carry semantic meaning and may not be modified by the design. Note that, while many of the design deliberations focus on the needs of the user, the needs of the designer must also be considered as the design is ultimately intended to be incorporated into a development framework. It must thus retain the flexibility needed to be adaptable for a variety of situations.

[liv] Note, of course, that a file system poses a similar difficulty, and that the Windows Explorer (Figure 23) is exactly such a tool for a file system.

As in the file system example, it is assumed that the basic metaphors of the environment must be retained—the two-dimensional surface and the continuous pan-zoom model of movement. The design is experimental and exploratory, so it is not necessary to conform to existing design conventions (although few such exist). The user is assumed to have "normal" physiology (vision, eye-hand coordination, etc.) as well as "normal" cognitive skills and resources (memory, attention, reasoning, etc.), and to be at least somewhat familiar with computers and the concepts and conventions of the interaction environment.

Task-Defined Structure

Definition of "Destination" and "Route"

As the task has been defined in this example, destinations in the task are individual objects on the surface. Note that an application designer might have more detailed information that allows this definition to be narrowed to objects that meet certain criteria—e.g., that match the query in a query-based search or that have been used recently—or that requires it to be expanded, for example, to include groups of objects. Thus, while the remainder of the design discussion will consider destinations to be single objects, an implementation to be included in an application framework should allow flexibility in the definition of destinations.

Routes are paths through space-scale (the conceptual space defined by the space-scale coordinate system). Because of the goal of retaining the pan-zoom model of movement, paths will be assumed to be continuous through space-scale. A designer, however, might wish to employ other types of routes, for instance, "hyperjumps" that allow instantaneous movement from one point in space-scale to another. Thus, a generalized implementation should allow for application-specific definition and selection of routes as well as destinations. This flexibility might allow definitions to be determined or selected dynamically and would offer the selection algorithms the opportunity to consider contextual information, such as mouse state and location.

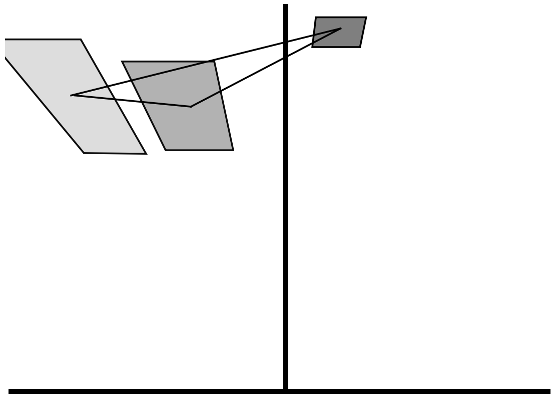


Figure 44 Task-defined structure for inter-object navigation in multiscale.

Shaded areas indicate objects, lines task-defined routes.

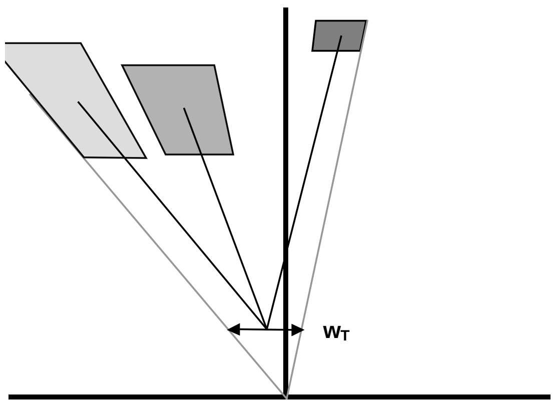


Figure 45 Object-based locomotional structure with the Top of the World branch region (**W_T**).

See *APPENDIX C Understanding Space-Scale Diagrams**, p. 299, for an explanation of space-scale diagrams.

Required Destinations and Routes

In the absence of detailed knowledge of the task, it must be assumed that any object in the environment is a potential destination and that all objects are equally likely to be the user’s intended destination at any given time. The latter assumption contrasts to the conclusion reached in the first design example, which resulted in a design in which differences in the likelihood of a file being the intended destination played a key role. It must also be assumed that the task does not intrinsically introduce any specific route requirements. Destinations are thus individual objects and routes are direct paths (i.e., paths with no branch regions) to destinations.

For the present purposes, direct paths will be modeled as “straight” lines through space-scale. It should be noted, however, that these may not actually represent the shortest paths between objects. Furnas and Bederson [82] posit that the shortest paths, in many cases, follow three-part space-scale trajectories that comprise a “straight-line” zoom-out, followed by a small pan and then a “straight-line” zoom-in. Such three-part paths can be substituted readily for simple single-part straight-line paths without compromising locomotional design considerations, and the simpler single-part paths will be assumed here for the sake of simplicity.

Supplemental Destinations and Routes

No non-wayfinding design goals have been specified, so no additional destinations or routes are indicated.

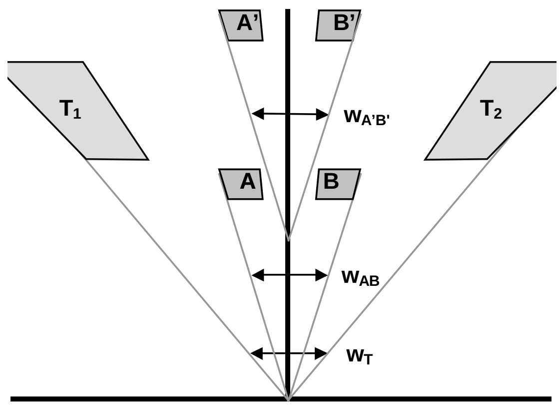
Task-Defined Structure

The task-defined structure of the inter-object navigation task, then, is composed of locations that contain individual objects and paths between any two such locations (Figure 44; See *APPENDIX C Understanding Space-Scale Diagrams**, p. 299, for an explanation of space-scale diagrams). This suggests an *object-based* locomotional structure that is defined relative to the geometry of objects in space-scale rather than a geometry-based locomotional structure, like the conventional locomotional structure (Figure 42 – Figure 43), that is relative to geometry of the space itself. The former reflects the assumption that the user is working in a populated environment and wants to go to where the objects are (or nearby). The latter is based on the assumption that the user is working in space-scale and may want to go anywhere in the environment.

Initial Design

Initial Locomotional Structure

Although the task-defined structure defines destinations as individual objects, experience with the design and development of spatial multiscale applications provides the insight that “locations” are best thought of as views of the surface. “Paths” are similarly thought of as trajectories through space-scale. The locomotional structure is therefore described as constituting views containing individual objects and paths that are straight space-scale trajectories.



$\mathbf{T_1}$ and $\mathbf{T_2}$ define outer boundaries of occupied space, thus determining the Top of the World view.

Object-pairs **AB** and **A'B'** have equivalent space-scale configurations, but are displaced in space and scale.

Let

$\Delta S(\mathbf{X}, \mathbf{Y})$	= Net distance to be traveled in scale to move from **X** to **Y**
$S(\mathbf{X})$	= Scale coordinate of location of **X***
$\mathbf{X} - \mathbf{Y}$	= Planar distance between **X** and **Y**
$\mathbf{w_{XY}}$	= The most magnified view containing both **X** and **Y**

*For the sake of simplicity, the following assumes that both objects have the same scale coordinate. If they differ, the calculations would be identical, but would use max(S(**X**), S(**Y**)) rather than S(**X**) where appropriate.

Shown by Furnas and Bederson [82],

(1) $S(\mathbf{w_{xy}}) = S(\mathbf{X}) - c \log (\mathbf{X} - \mathbf{Y})$

By construction,

(2) $S(\mathbf{A}) \neq S(\mathbf{A'})$

(3) $S(\mathbf{A}) - S(\mathbf{w_{AB}}) = S(\mathbf{A'}) - S(\mathbf{w_{A'B'}})$

Unrestricted Zoom

In unrestricted zoom, it is only necessary to zoom out to $\mathbf{w_{XY}}$ in order to move from **X** to **Y,** thus:

$$\begin{aligned} \Delta S(\mathbf{A}, \mathbf{B}) &= S(\mathbf{A}) - S(\mathbf{w_{AB}}) \\ &= S(\mathbf{A'}) - S(\mathbf{w_{A'B'}}) \qquad (3) \\ &= \Delta S(\mathbf{A'}, \mathbf{B'}) \end{aligned}$$

Top of the World Zoom

In Top of the World zoom, it is always necessary to zoom out to the Top of the World ($\mathbf{w_T}$), thus:

$$\begin{aligned} \Delta S(\mathbf{A}, \mathbf{B}) &= S(\mathbf{A}) - S(\mathbf{w_T}) \\ &= S(\mathbf{A}) - (S(\mathbf{T_1}) - c \log (\mathbf{T_1} - \mathbf{T_2})) \qquad (1) \\ &= S(\mathbf{A}) - S(\mathbf{T_1}) + c \log (\mathbf{T_1} - \mathbf{T_2}) \end{aligned}$$

Similarly,

$$\begin{aligned} \Delta S(\mathbf{A'}, \mathbf{B'}) &= S(\mathbf{A'}) - S(\mathbf{T_1}) + c \log (\mathbf{T_1} - \mathbf{T_2}) \\ &\neq \Delta S(\mathbf{A}, \mathbf{B}) \qquad (2) \end{aligned}$$

In unrestricted zoom, the net distance to be traveled in scale to move between two objects is thus a function only of the planar distance between them. In Top of the World zoom, however, it is a function of the planar distance between the objects defining the Top of the World boundaries and the distance in scale between the boundary objects and the origin or destination object.

Figure 46 Proof that unrestricted and Top of the World zoom may result in different route lengths.

An actual locomotional structure that corresponds to the task-defined structure can be produced by using the existing locomotional mechanism, but restricting movement. At any destination view, the user may select another destination and the view is automatically moved to the selected destination by following a direct space-scale trajectory. This corresponds to the locomotional structure shown in Figure 44. Note that the resulting paths are, in most cases, composite pan-zoom trajectories that are computed automatically by the system and are not controlled by the user. As there is no natural means of providing information about all options, this must be handled through prosthetic informational design, for instance, by presenting a visual menu of possible destinations.

Applying Design Principles

Principle 1 Locations and Paths

The locations and paths offered by the locomotional structure must be a superset of the destinations and routes in the task-defined structure.

The locomotional structure defined thus far (Figure 44) was derived directly from the task-defined structure, so the two are identical and this principle is satisfied.

Principle 2 Number of Branch Regions

Increasing the number of branch regions in the locomotional structure is likely to increase wayfinding difficulty, and decreasing the number is likely to decrease difficulty.

The goal is to make wayfinding as simple as possible, so the number of branch regions should be made as small as possible. The number of branch regions in the currently proposed locomotional structure is N_{filter}; the number of objects selected as potential destinations. (Although the present design considers all objects to be potential destinations, the “filter” subscript is used to indicate that a generalized implementation allows more specialized selection to be performed.) This can be reduced to a single branch region by introducing a location from which all objects can be reached. Unlike in the file system design where the desktop was system-defined, all of the destinations in the task-defined structure are user-defined and cannot be depended upon to exist to provide reliable access to other locations. It is thus necessary to develop a stable location that is guaranteed to exist and from which other locations can be reached.

Experience with multiscale environments suggests selecting a view that contains[lv] all objects. The obvious view to select is the Top of the World—the most magnified such view. If the user is moving between existing objects, zooming out beyond this view is extraneous and increases the distance to be traveled unnecessarily. (Of course, provisions must be made for doing so when the task of adding or moving objects is considered.) Adding the Top of the World branch region allows routes between objects to be eliminated, and reinstates a "zoom out to zoom in" model of movement that is more consistent with multiscale interaction expectations. This results in the *object-based* locomotional structure shown in Figure 45. This structure has one branch region with N_{filter} options.

As the Top of the World view is unique with respect to a given object layout and window configuration, any movement—whether in planar or scale dimensions—will depart from the view. The Top of the World branch region thus, like branch regions in the Repeat File Access design, has no extent in the direction of movement and entry and exit ports coincide. Note that, because all objects, by definition, are contained in the Top of the World view, information about options may be created simply by showing the extension through scale of objects that are not inherently visible.

It is immediately apparent to anyone with experience with zooming user interfaces, however, that this is not a satisfactory locomotional structure. Zoom and pan movement is not instantaneous, but increases with the distance traveled. In pure zooming movement, the space-scale distance to be traveled between two points is logarithmically related to the planar distance between them [82]. By forcing users to zoom out to the Top of the World to move between any two objects, travel time becomes related to the greatest planar distance between any two objects in the layout and the distance in scale between

---

[lv] "Containing" here defined as the object being located within the portion of the surface that is bounded by the view window, regardless of whether it an actually be seen.

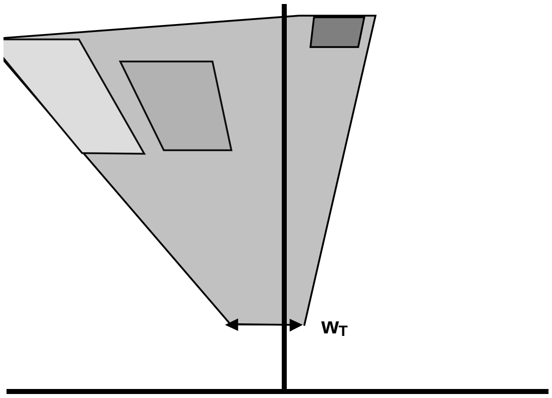


Figure 47 Region-based locomotional structure with one intermediate branch region in addition to the Top of the World branch region.

Movement is constrained to the shaded region.

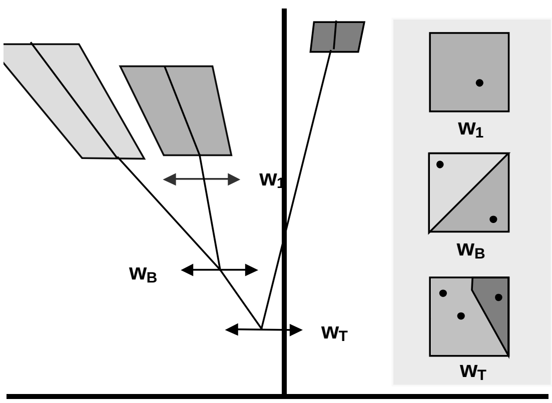


Figure 48 Cluster-based locomotional structure.

Movement is constrained to follow the indicated paths.

Schematics on the right show possible surface views at the indicated locations. Shading indicates locomotional options with mouse-proximity steering.

these objects and the origin or destination object (Figure 46). This not only introduces unnecessarily long paths but also violates users' intuitive expectations of path length.

One means of preventing users from having to travel unnecessarily long paths is to allow movement to stop between the Top of the World and destination views, i.e., to return to a more standard, interruptible model of zooming. While movement is still constrained to move either toward the Top of the World or an individual object, users are able to stop at intermediate locations and select a different target location. This creates a single intermediate branch region (N_{filter} + 1) options: N_{filter} that lead to views of single objects and one that leads to the Top of the World.

The intermediate branch region comprises the space-scale region bounded by the convex hull of all objects and the Top of the World, but not including the *End of Object views*—the most magnified views in which objects can be seen—or the Top of the World (Figure 47). The End of Object views offer only one locomotional option (leading to the Top of the World), so are not branch regions, and the Top of the World constitutes a distinct branch region offering only the N_{filter} options leading to objects. The entry and exit ports of the intermediate branch point coincide and are the views seen immediately before reaching an End of Object view or the Top of the World.

Since movement can only move toward an End of Object view or the Top of the World, overall movement is limited to the space comprising intermediate branch region, all End of Object views and the Top of the World. Since movement can stop at any time, however, it is possible to reach any point in this area by alternating short zoom-in and zoom-out movements. This is in contrast to the initial object-based structure where it is not possible to reach points that are not on a straight space-scale trajectory between an object and the Top of the World (Figure 45). This *region-based* locomotional structure, consequently, has two branch regions and does not impose unnecessarily long paths. Note that presentation of options at the intermediate branch region cannot rely on simply extending objects through scale (as is possible at the Top of the World), and some more sophisticated synthetic informational design must be used.

An alternative means of introducing intermediate branch regions is to use the relative spatial positioning of objects. It is likely that spatial positioning is not random, but that groupings reflect semantic meaning, so movement that is defined in terms of spatial groupings is likely to be meaningful to the user. A variety of spatial cluster analysis techniques [74] have been developed that may identify such groupings. One of the simpler methods, for example, uses a simple distance metric (e.g., the distance between the centers of object bounding boxes) to group objects and object groupings using pairwise comparison. Used recursively, this method yields a binary tree of hierarchically nested groups. The *Top of a Group* view—the most magnified view containing the group—may then be treated as a branch region. These views are (like the Top of the World) uniquely defined with respect to a particular object layout and window configuration, and have no extent in a direction of movement. Entry and exit ports of these branch regions thus coincide.

Movement in this c*luster-based* locomotional structure is constrained to move between the Tops of Groups or between the Top of a Group and an End of Object view, i.e., between levels of the nesting structure. Zoom-in descends (moving to a detailed view of a subgroup or object) and zoom-out ascends the corresponding tree (Figure 48).

The particular clustering algorithm applied determines the number of clusters and their relative containment. Assuming, for illustration, that a clustering algorithm that yields a tree is used (Figure 60). The number of clusters—equivalent to the number of branch regions—corresponds to the number of internal nodes of the tree (leaf nodes correspond to single object views, and, thus, do not constitute branch regions). If the simple binary algorithm is used, for instance, the maximum number of branch regions is thus (N_{filter} – 1). The number of options in each branch region corresponds to the branching factor of the tree. In the case of the binary tree, each branch region has exactly two options.

Regardless of which approach for introducing intermediate branch regions is used, the resulting locomotional structure has far fewer branch regions than the conventional locomotional structure. The conventional geometry-based locomotional structure has an infinite number of branch regions: Each pixel in the view window represents a locomotional option. Each view presents a unique set of pixels, i.e., is a unique branch region, and there are, conceptually, an infinite number of views. Since movement is not guaranteed to lead to an object or even to an inhabited region of the environment, informational design generally is the only means of preventing users from getting lost. (This is confirmed by the *Desert Fog* experiment reported in Chapter 5.)

Principle 3 Complexity of Branch Regions

The fewer options offered in a branch region, the simpler the wayfinding will be.

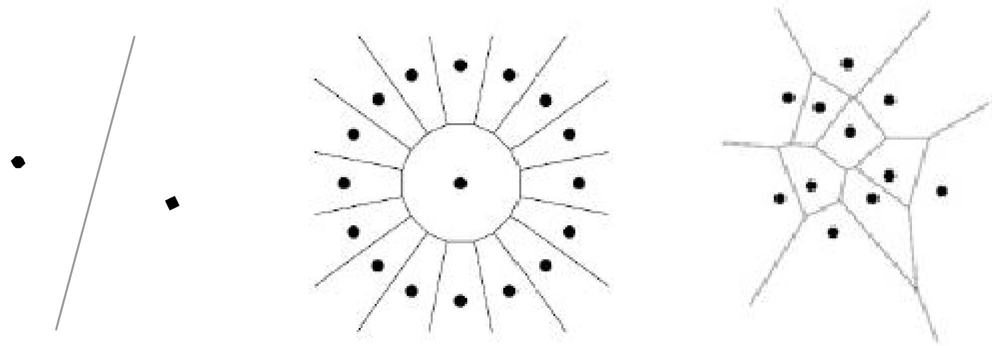
The two possible locomotional structures developed thus far, region-based (Figure 47) and cluster-based (Figure 48), have, as discussed, two and (N_{filter} – 1) branch regions, respectively. The two branch regions of the object-based structure, the Top of the World and the intermediate branch region, have N_{filter} and (N_{filter} + 1) options, respectively. Branch regions in the cluster-based structure, in contrast, have exactly two options (assuming a binary clustering algorithm). Thus, while the number of options in branch regions in the cluster-based structure seems acceptable, a means of reducing the number of options or decomposing the intermediate branch region is needed for the object-based structure. (Note that the underlying assumption of the relevance of spatial groupings limits the generality of the cluster-based structure. It is thus desirable to continue to pursue both designs.)

Mouse-Proximity Steering

The region-based structure, as has already been observed, depends on sophisticated synthetic informational design to present options in the intermediate branch region. By definition, none of the views in this branch region contains all options naturally, so this must rely on prosthetic design, e.g., a menu of options. Such indirect interaction is inconsistent with the philosophy of direct manipulation (cf. *File System Interaction*, p. 186), which underlies the design of Jazz, and seems particularly awkward in the case of spatial interaction. A more consistent approach would be to allow users select the desired option directly by using the mouse. This is also more consistent with standard conventions of Jazz interaction.

However, allowing users to select their destination by clicking directly on the target object not only prevents them from reaching destinations that are not in the view, but also leaves large portions of the surface inert. These difficulties suggest a steering design that allows “approximate” clicking. That is, if the user clicks on an unoccupied portion of the surface, the system will assume that the object closest to the mouse is the intended target. (“Closest,” in the present design, is defined in terms of planar distance, but other distance metrics could readily be employed, indicating that a general implementation should allow for application-specific definitions.) Such *mouse-proximity steering* allows users to select destinations that are not in the view, and, in accordance with *Principle 12 Steering and Locomotional Structure* (p. 190), reduces the required precision of steering actions.

Note that mouse-based-proximity steering can only be used for zoom-in. If zoom-out destinations were considered, these would always be selected: By definition, the entire view is always contained within a zoom-out destination, so any point in the view is coincident with a point in the zoom-out design. The zoom-out destination would thus always be “closest.” Zoom-out option is therefore separated from zoom-in options and the user is required to indicate their desired direction of zoom, e.g., by using different mouse buttons. If the zoom-out direction is selected, there is one possible destination.



Dots indicate sites, lines indicate cell boundaries.

Figure 49 Examples of Voronoi diagrams.

Selection of direction is thus sufficient and no further means of zoom-out option selection are needed.

Although developed for the region-based locomotional structure, mouse-proximity steering can also be used with the cluster-based structure. Here, of course, the nearest object group, rather than the nearest object, will be selected as the zoom-in destination. The zoom-out destination will always be the smallest Top of Group branch region that contains the current view.

Voronoi-Based Locomotional Structure

Mouse-proximity steering changes the fundamental characterization of branch regions. In both region- and cluster-based designs, branch regions are determined entirely by the object layout, although their exact size and location in space-scale also depends on window configuration. For instance, the number of Top of Group branch regions and their options in the cluster-based design are dictated entirely by the relative positions of objects.

When using mouse-proximity steering alone (i.e., not with the cluster-based structure), however, the number of branch regions and their options depend on a combination of object layout and window configuration: If two objects are outside the current view and one is further away, in the same direction, as another, the latter will “block” the former. In this case, the locomotional options offered by the branch region

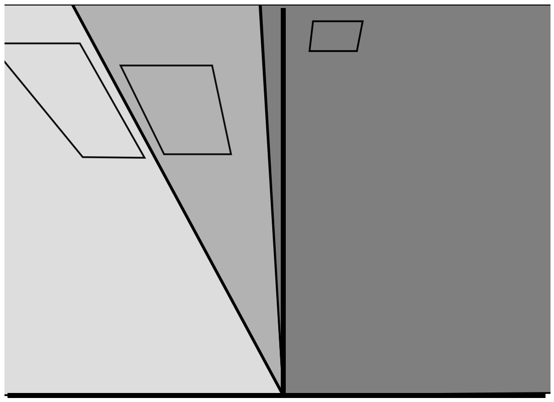


Figure 50 Planar Voronoi cells arising from object placement.

Shading shows areas in space-scale in which a given object is always the closest.

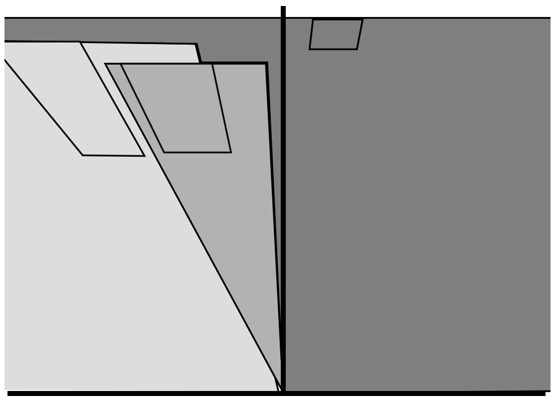


Figure 51 Zoom-in Voronoi cells.

Only objects that can be reached (i.e., seen in a view) by zoom-in are considered.

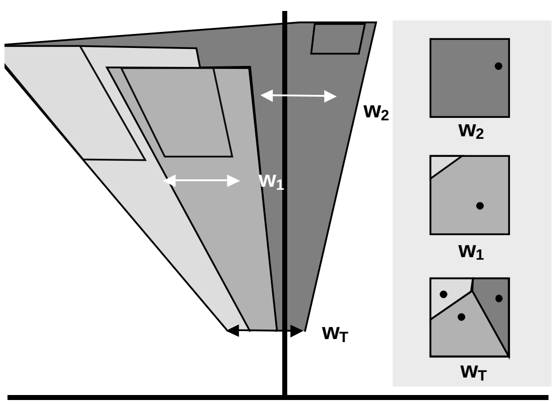


Figure 52 Zoom-in Voronoi cells within the destination-targeted region of space-scale.

Only objects that can be reached by zoom-in, and only space-scale points that can be reached by destination-targeted movement are considered.

Views that intersect region boundaries offer multiple locomotional options.

Schematics on right show possible views. Shading indicates locomotional options.

containing the current view do not include the second object. If one of the objects is moved, so that the two objects are not collinear with respect to the current view, it is possible to reach both of them, i.e., the second object is included among the options of the current branch region. The option leading to the second object can also be added by changing window size (without changing the object layout) so that the first object is within the current view. Rather than posing a difficulty, this characteristic decomposes the intermediate branch region of the object-based structure, resulting in the *Voronoi-based locomotional structure*.

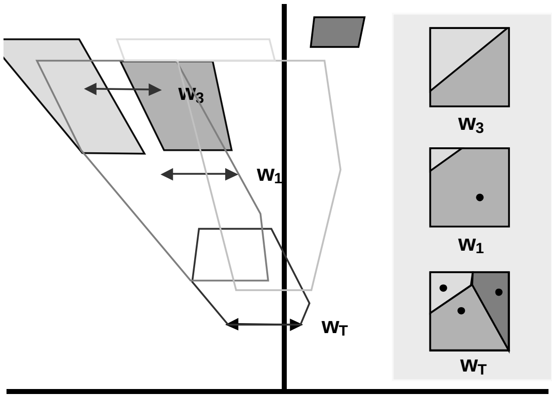


Figure 53 Zoom-in branch regions in Voronoi-based locomotional structure (scale view).

Outlines show branch regions. The area that contains the view window fully is the current branch region. Ports occur where branch region boundaries do not coincide with the convex hull of object layout (the shaded area in Figure 52).

Diagrams assume that the center of the view window always moves toward the center of the object or branch region. This limits movement to the shaded areas.

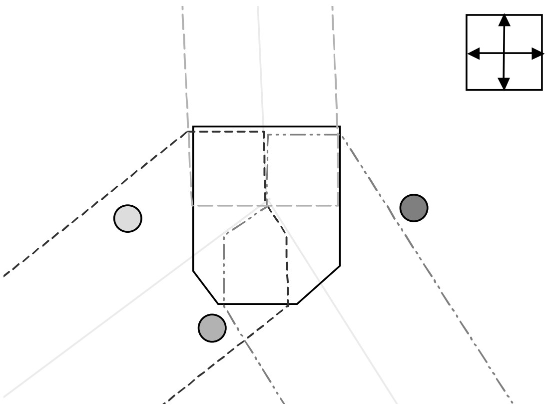


Figure 54 Zoom-in branch regions in Voronoi-based locomotional structure (planar view).

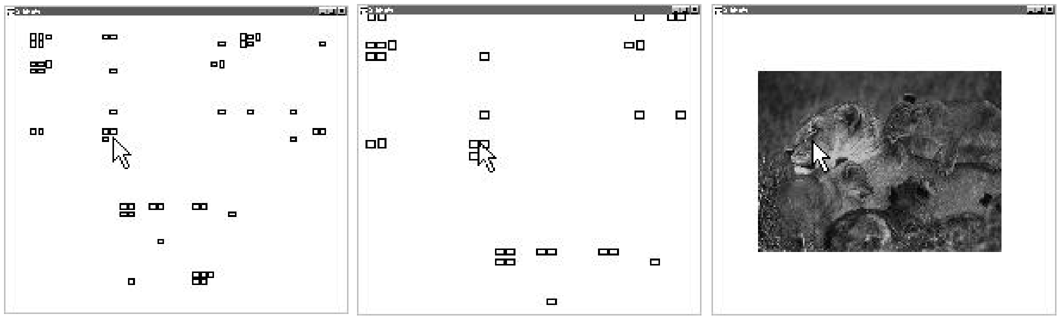
Shaded circles indicate objects, shaded lines show individual branch regions, and lightest gray lines show Voronoi cell boundaries. The area that contains the view window fully is the current branch region.

Rectangle at upper left shows assumed size of viewing window.

A *Voronoi diagram* is a tessellation of a Euclidean plane containing n *sites* (objects, in the present case) into n *Voronoi cells or regions* [60]. Each cell is defined by a particular site and comprises all points on the surface that are closer to that site than to any other (Figure 49).

In spatial multiscale, the layout of objects on the surface defines a Voronoi diagram (Figure 50). These planar Voronoi cells are truncated in scale when only objects that can be reached by zoom-in are considered, i.e., when the distance in scale to the object must be greater than 0 (Figure 51). As view scale increases, planar dimensions of individual cells may be subject to sudden expansions, since objects may have different extents in scale, i.e., have different maxscale[lvi] values, (Figure 51). In a general Voronoi diagram, some cells may be bounded (i.e., have a finite area), but the "outer" cells are always

[lvi] The maximum magnification at which an object is visible (cf. *Appendix B Understanding Space-Scale Diagrams*).



Top of the World

Zoom-In: The user clicks on or near the object to which they want to go. Zooming moves toward the object that is closest in space-scale to the mouse.

Zoom-out: Zooming stops at the Top of the World.

Intermediate Branch Region

Zoom-In: Movement automatically continues toward the nearest target, when branch regions are automated. If they are not, zooming stops and the user must re-initiate movement manually.

Zoom-out: Zooming moves or continues automatically toward the Top of the World.

End of Object

Zoom-in: Zooming stops when the target is reached, in this case, a photograph on the surface.

Zoom-out: The user clicks anywhere. Zooming moves toward the Top of the World.

Object outlines shown for illustration—visual design is part of informational design.

Figure 55 Interaction with a Voronoi-based locomotional structure with automated branch regions.

unbounded[lvii] (Figure 50). When movement is constrained to move toward a destination, however, overall movement is restricted to a bounded area of space-scale (Figure 47). All zoom-in Voronoi cells are consequently bounded (Figure 52).

With the mouse-proximity steering design, a user must click within the zoom-in Voronoi cell defined by an object to reach that object. The set of locomotional options available at a particular view thus corresponds to the set of Voronoi cells that intersect the viewing window (Figure 52, schematics on right). Branch regions in the Voronoi-based locomotional structure are thus contiguous areas of space-scale in which all views

---

[lvii] As a Voronoi diagram represents the intersections of N half-planes, it follows that some intersections must be unbounded.

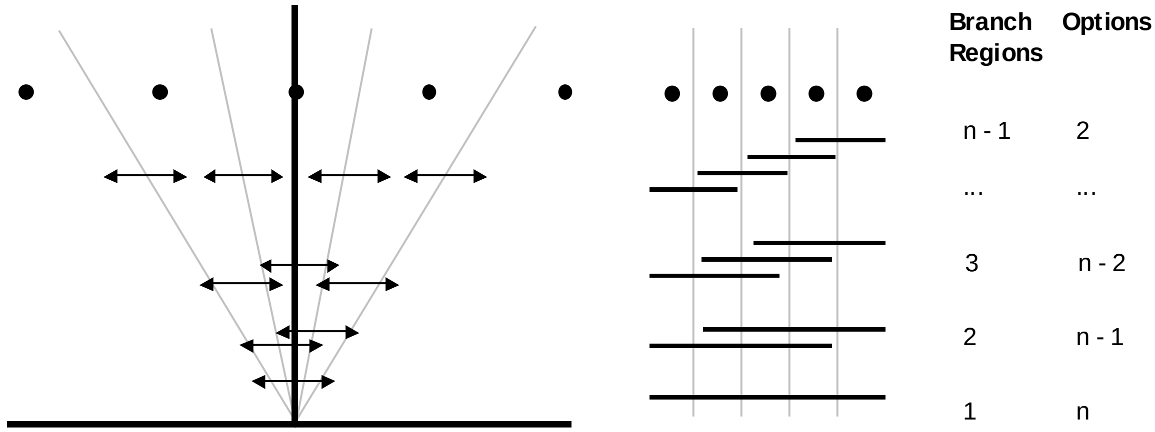
intersect the same set of Voronoi cells. (Note that it does not matter how much of a Voronoi cell is within the viewing window or where it located is with respect to the window center.) Because of the properties of planar geometry, it is not possible for two windows to intersect the same set of Voronoi cells unless all views between them also intersect that set of cells. Therefore, if two views intersect the same set of cells, they are part of a single branch region. The options offered by that branch region correspond to the objects that are represented by intersected cells.

Figure 53 shows a space-scale diagram of the Voronoi-based branch regions in an example layout. Figure 54 shows a simple planar diagram of the branch regions for the same layout. Interaction with the resulting Voronoi-based structure is illustrated in Figure 55 (assuming non-automated branch regions; automation of branch regions is discussed later in *Automated branch regions*, p. 220).

Complexity of Voronoi-Based Structure

Since the Voronoi cells completely partition the surface, it is not possible for a view not to intersect at least one cell. If it intersects two or more cells (i.e., it is in a branch region), the boundaries between these cells must intersect the viewing window. Any view that intersects a Voronoi cell boundary is therefore in a branch region, and all views that intersect the same cell boundaries are in the same branch region. The number of branch regions in the locomotional structure thus corresponds to the number of ways in which a rectangular viewing window can intersect Voronoi cell boundaries (Figure 57 bottom), and the number of options to the sum of the number of cells a window in each branch region intersects.

Due to the complexities of Voronoi geometry, calculation of the actual (or even maximum) number of branch regions and branch region options in the Voronoi-based structure is a mathematically difficult problem and will not be attempted here. (A complete statement of the problem may be found in *APPENDIX E Voronoi Problem Statement*, p. 303). However, an example provides some general indications (Figure 57, Figure 56).



Dots represent objects, gray lines show Voronoi cell boundaries, and black lines show branch region entry ports. The diagram on the right shows a Mercator-like projection of the space-scale diagram on the left. The columns on the right show number of branch regions with a given number of options.

From this diagram, it may be seen that, for a layout in which objects are collinear, the number of branch regions is

$$\sum_{i=1}^{n-1} i = \frac{(n-1)(n-1+1)}{2}$$

$$= \frac{n^2 - n}{2}$$

and the number of branch region options is

$$\sum_{i=1}^{n-1} i(n-i+1) = \sum_{i=1}^{n-1} in - i^2 + i$$

$$= (n+1)\sum_{i=1}^{n-1} i - \sum_{i=1}^{n-1} i^2$$

$$= (n+1)\frac{n^2 - n}{2} - \frac{(n-1)(n-1+1)(2(n-1)+1)}{6}$$

$$= \frac{n^3 + 3n^2 - 4n}{6}$$

Figure 56 Number of branch regions and branch region options in Voronoi-based structure with collinear object layout.

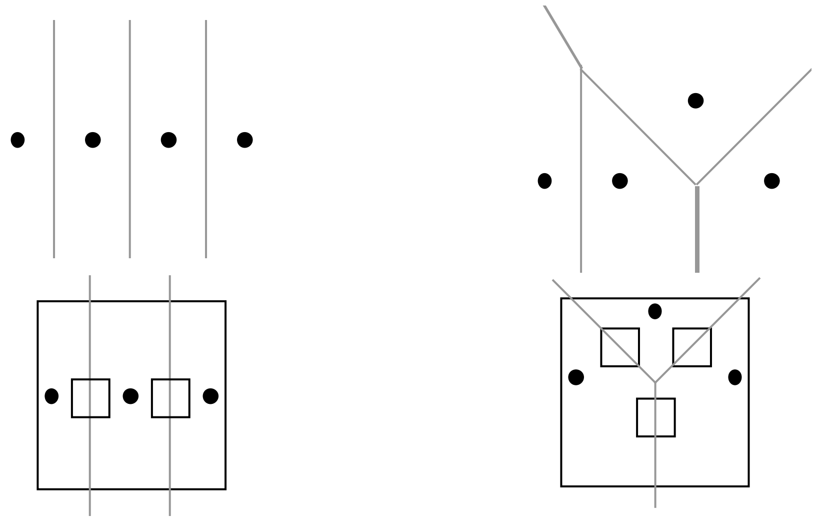
Figure 56 shows that a collinear layout with objects has $\frac{N_{filter}^{2} - N_{filter}}{2}$ branch points and $\frac{N_{filter}^{3} + 3N_{filter}^{2} - 4N_{filter}}{6}$ branch point options, i.e., $O(N_{filter}^2)$[lviii] and $O(N_{filter}^3)$, respectively. While object layouts may exist that have fewer branch points than this—although any layout must have at least $(3N_{filter} - 6)$[lix] branch regions, collinear layouts or layouts with collinear sublayouts can be expected to be somewhat common, particularly if they are generated algorithmically. Figure 57 shows that a non-collinear layout is likely to have even more branch regions and more branch region options than a collinear layout of the same number of objects. Whether this results in an increase in the order of magnitude of the number of branch regions is as yet unknown. (The reader will be tempted to calculate the number of rectangles that can enclose subsets of the N sites uniquely. The problem, however, requires calculation of the number of rectangles that can intersect the Voronoi boundaries uniquely. (Cf. *APPENDIX E Voronoi Problem Statement*, p. 303.)

However, it is likely that the Voronoi-based structure of an arbitrary layout has at least $O(N_{filter}^2)$ branch regions and $O(N_{filter}^3)$ branch region options. This is considerably fewer branch regions than the infinite number of the conventional geometry-based locomotional structure: In the geometry-based structure, zoom-in leads to a different view depending on which pixel was selected as the center of the zoom. As each view is a branch region, each branch region has w * h zoom-in options, where w and h are the width and height, respectively, of the view window in pixels. Branch regions in the Voronoi-based structure thus also have considerably fewer options than branch regions in the geometry-based locomotional structure. Nonetheless, the Voronoi-based structure has considerably more than the $(N_{filter} - 1)$ branch regions of the cluster-based structure

---

[lviii] So-called “big-O” notation is used to describe an upper limit on how rapidly a number can grow. Informally, saying some function f is the order of some function g, f(n) = O(g(n)), means that f(n) is less than some constant multiple of g(n).

[lix] The minimum number of edges in a 2-dimensional Voronoi diagram [60].



Dots indicate object locations, gray lines Voronoi boundaries. In the bottom row, the large and small square boxes show representative viewing windows for different branch regions, each touching on a distinct set of Voronoi regions. Note that these are planar (rather than space-scale) diagrams, so window size appears to change.

***Top left**:* In a collinear object layout, the two "end" regions have one neighboring region each, while all others have two.

***Top right**:* If one object is not collinear with the rest, the two "end" regions have two neighbors, while others may have more than two. *Heavy lines indicate added boundaries.*

***Bottom**:* A collinear layout of three objects offers three different branch regions (left), whereas a non-collinear layout of objects allows four (right). (Cf. Figure 56 for a general formula for the number of possible branch regions in the collinear case.)

Figure 57 Illustration of effects of non-linear positioning on increasing the number of branch regions.

(Figure 58). Additionally, most of the Voronoi-based branch regions are likely to have more than the two options of the cluster-based branch regions.

In fact, considered in absolute terms, the number of branch regions in the Voronoi-based structure rapidly reaches values that seem unwieldy. For example, a collinear layout of a mere 50 objects has 1225 branch regions! Although the psychological evidence surrounding plan complexity (Chapter 3, *Plan Complexity*, p. 135) does not indicate how many branch regions are too many, such numbers far exceed those of the layouts reportedly used in most studies. This evidence raises the expectation that the

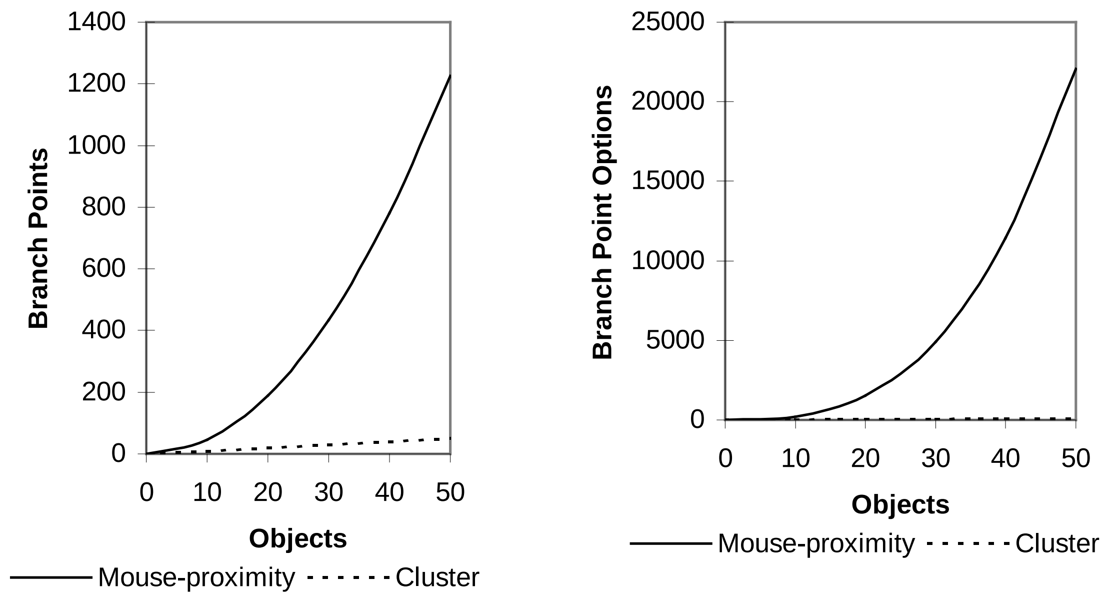


Figure 58 Increase in number of branch regions in mouse-proximity- and cluster-based structures, assuming a "simple" collinear layout.

Voronoi-based structure poses significant wayfinding difficulties and should be abandoned. Intuitively, however, it seems promising and worth further investigation.

Principle 12 Steering and Locomotional Structure

The fewer or less precise steering actions that are required to follow the selected route and to remain within the locomotional structure, the fewer wayfinding errors are likely.

Since the relationship between steering design and locomotional structure has already been introduced, the principle relating the two is considered now, although it may seem out of order. The mouse-proximity steering design already described implies that movement stops at branch regions—either at an entry or exit port or somewhere within the region—and requires the user to select an option in order to continue. However, because zoom direction is indicated by which mouse button is pressed and target destination by mouse position, it is not necessary for movement to stop to allow the user to select an option.

The mouse-proximity steering design is thus enhanced to allow the user to change the targeted destination at any point after passing the entry port and before passing the exit port by moving the mouse to be closer to a different object. If they do not move the mouse yet indicate their intent to continue zooming by not releasing the button, it is assumed that they desire to continue moving toward the current target and the appropriate option is selected automatically. This modification allows users to pass through branch regions using fewer steering actions as well as allowing them to select a different option using fewer actions (Figure 64).

While automatic selection of an option at a branch region may simplify the steering actions required to follow a route, it may also increase the number of steering actions required. If the default option—the automatically selected option—is a correct one, the user need take no action at the branch region. If, however, the default option is not correct, the user must not only perform the actions necessary to selecting a correct option, but may also have to perform additional actions to correct an erroneous selection.

Logically, it would seem that the cognitive overhead of passing the branch region should be affected similarly. That is, if the default option is a correct choice, the user may proceed without having to consider what options are available—potentially even without noticing that a branch region has been passed. Conversely, the cognitive overhead is likely to be increased if the default option is incorrect, since the user must not only consider the available options and select a correct one but must also recognize that has or is about to occur and take steps to address it. These considerations suggest the existence of a further design constraint that may be formulated as a design principle:

Automated branch regions
• A branch region is ***automated*** if no steering action is required to select an option.
• The option selected if no steering action is taken in an automated branch region is the ***default*** option of that branch region.
• A branch region is ***well-automated*** if the default option is the expected and desired option with respect to the user's goals.
• A branch region is ***poorly-automated*** if the default option is not the expected and desired option with respect to the user's goals.
• A non-automated branch region is also known as a ***manual*** branch region.

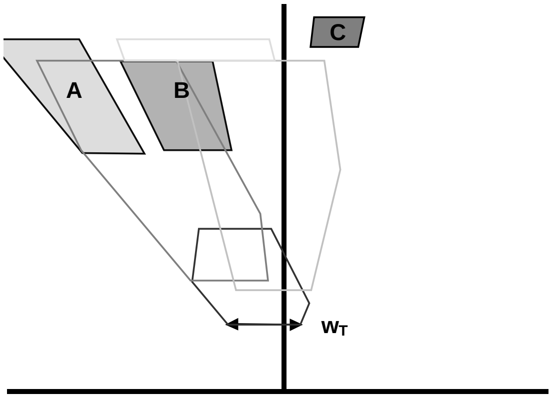
13. Automated branch regions

An automated branch region decreases the difficulty of wayfinding if it is well-automated, but increases the difficulty if it is poorly-automated.

The automated branch region constraint is neither supported nor disproved by existing psychological evidence, as the effect of automatically selected options on wayfinding cognition does not appear to have been studied. Most wayfinding studies focus on locomotional mechanisms that require active steering at all times, such as walking or driving a car. However, much design, particularly of electronic environments, concerns ways of finding and providing the “right” default values or actions. The lack of empirical evidence may be due to the difficulty of automating option selection in the physical world (the switching of trains being, perhaps, the only commonplace example) or it may be that this is a question that has greater import for design than for psychological understanding. Regardless, this principle may be regarded as a psychological hypothesis the testing of which is demanded by design, if not by psychology.

Use of the object that was initially closest to the mouse to select the default zoom-in option is consistent with mouse-proximity steering. In the Voronoi-based structure, an intermediate target is also a final destination. As destination-targeted movement brings the target closer to the mouse as zoom-in progresses, the intended destination will remain the option closest to the mouse, if it was the closest initially. Thus, if this type of automation is combined with mouse-proximity steering, the user will obtain the same results if they stop at branch regions and click again without moving the mouse, as they will if they rely on automated option selection.

Whether zoom-in branch regions are well- or poorly-automated depends on the user’s initial selection: If the initial selection was correct, all zoom-in branch regions are guaranteed to be well-automated, whereas if it was incorrect, they are guaranteed to be poorly-automated. How accurately the user can be expected to anticipate the position of the target relative to the initial view can only be determined by the designer using knowledge specific to the design situation.



(Figure 53 Reproduced for ease of reference. branch regions shown are those of the Voronoi-based structure.)

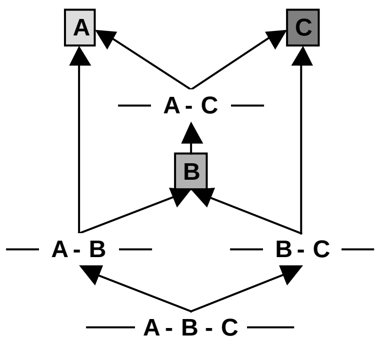


Figure 59 Lattice organization of Voronoi-based locomotional structure corresponding to the layout presented in Figure 53.

Arrows show paths, letters indicate branch region options, and shaded boxes actual objects.

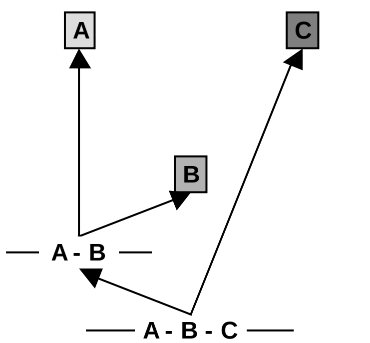


Figure 60 Hierarchical organization of cluster-based locomotional structure corresponding to the layout presented in Figure 53.

In the cluster-based structure, however, intermediate targets are object groupings. Although the final target is part of an intermediate group target, there is no guarantee that it will be the object that is closest to the mouse either initially or when the group is centered on the screen. Thus, if this type of automation is combined with mouse-proximity steering in the cluster-based structure, the user may not obtain the same results by stopping and clicking again as they will if they rely on automated option selection. In Figure 48 (p. 206), for example, if the user clicks directly on the center object at the Top of the World branch region, the view will move to the branch region at w_B where the left object is closer to the initial mouse location. The present work offers no prediction of whether the discrepancy between manual and automatic selection would be a benefit or source of difficulties for users.

As branch regions in both structures have at most one zoom-out option, zoom-out can be automated readily in both structures if it is separated from zoom-in, e.g., by assignment to a different mouse button. With only one possible option, such automation is guaranteed to be well-automated.

Principle 4 Task Logic and Organizing Principle

The more closely the logic of the organizing principle of the locomotional structure corresponds to the logic of the task, the less overhead is introduced by wayfinding cognition.

The obvious and, at this point in the design, the only known logic driving multiscale interaction is the spatial geometry of object layout and of space-scale. Other logics are possible, but must be determined by the designer using task-specific knowledge. For example, the task might suggest a structure that is based on spatial distribution of non-spatial properties of objects. Such a structure might have spatially overlapping groups, a situation that is not considered by either of the approaches outlined here. Regardless of the logic of the task, however, the nature of spatial multiscale interaction guarantees that it be manifest spatially.

The organizing principles of both proposed locomotional structures are based on the spatial layout of objects. The Voronoi-based structure results in a lattice structure that reflects the topography of objects (Figure 59). Branch regions and paths in this structure depend on the relative positions of objects in space-scale. Distance between objects does not affect the determination of branch regions and paths, but determines only the positioning of branch regions in scale. The cluster-based structure imposes a hierarchical interpretation on the object layout (Figure 48), resulting in a hierarchical organizing principle (Figure 60). This structure is determined by the distance between objects, but is unaffected by their relative positioning.

Both structures thus offer organizing principles that are sufficiently general to match a variety of task logics, albeit in very general ways. It is up to the designer to determine which, if either, is better suited and what adaptations might be necessary. As most task logics are likely to involve objects rather than space-scale, either of the structures proposed here are more likely to be suitable than the conventional geometry-based locomotional structure (defined relative to space-scale geometry). The lattice structure of the Voronoi-based approach may be more flexible and may thus be adaptable to a broader range of tasks. The hierarchical structure of the cluster-based approach, while suited to fewer tasks, is likely to meet the needs of those tasks more precisely than the mouse-proximity structure meets the needs of the tasks for which it is suitable.

Branch Regions Revisited

Exposing the lattice structure of the Voronoi-based structure invites reconsideration of the implications of its seemingly excessive numbers of branch regions. The lattice structure reveals that the additional branch regions represent alternative routes to destinations (Figure 59). For example, whereas there is exactly one route to each destination in the cluster-based structure in Figure 60, the lattice structure in Figure 59 offers three routes to each of objects **A** and **C**, and two to object **B**. These alternative routes may increase the likelihood of wayfinding success. For instance, in the lattice structure in Figure 60, 3/8 of the routes offered lead to **A** (**C**), and 4/8 to **B**. In contrast, in the hierarchical structure only 1/3 of the routes lead to each object.

Although the alternative routes may increase the number of decisions the wayfinder has to make (depending on the actual route selected), they may decrease the number of correct decisions they have to make or the total number of options they have to consider. For example, in the hierarchical structure in Figure 60, two correct decisions are required to reach object **B**, while only one is required in the lattice structure of Figure 59. In order to reach object **A**, the wayfinder has to make two correct decisions in either case, but is presented with a total of four options in the lattice structure and five in the hierarchical case. Only in the case of object **C** are both the number of correct decisions and the number of options to be considered increased.

Not only is there an increased number of routes to the destination, but the alternative routes are clustered around the shortest route. That is, the closer a decision is to being optimal (in this case, leading to the shortest route), the higher the likelihood is that it will be a correct decision. Thus, along much of the route, wayfinders need only approximate the best choice in order to complete their task.

Consequently, the increased number of branch regions may decrease wayfinding performance, but increase the likelihood of wayfinding success. The increased chances of wayfinding success may account for the design intuition surrounding the promise of the Voronoi-based structure, while the flexibility offered by the redundant routes may account, in part, for the impressive empirical results obtained in actual studies (reported in Chapter 5). This suggests the formulation of a further design principle:

14. Alternative Routes

Alternative routes to destinations may decrease wayfinding performance, but increase the likelihood of wayfinding success, particularly if they are clustered around the optimal route.

This principle, again, represents an untested psychological hypothesis that is of value to design, but which has not been of sufficient importance to psychology to be tested. This may reflect fundamental differences between human-computer interaction and psychology: Where the latter usually seeks to understand optimal behavior, the former seeks to support usability, i.e., successful behavior. For example, all of the studies described that investigated the effect of plan complexity on wayfinding behavior and performance (Chapter 3, *Plan Complexity*, p. 135) regarded any deviation from the shortest path as erroneous behavior, or ensured that alternate paths were not available. In design, it is generally more important to ensure successful behavior, even at the cost of imposing less than optimal performance. Optimal behavior is often treated as a special case and is supported in design for so-called “power users.”

Principle 5 Simplicity of Organizing Principle

Within the organizing principles made possible by the task, the simpler the principle, the simpler the wayfinding

Both proposed organizational principles are based on the topography of objects and are computationally simple. The lattice structure of the Voronoi-based structure may be difficult for users to discover, but is expected to be simple to use. In practice, users are expected to concentrate on immediate substructures and these may be interpreted as hierarchical without causing erroneous behavior. The hierarchical structure of the cluster-based structure is familiar to many, especially to computer users. Both structures are thus expected, in practice, to be simple for humans. Additionally, both are consistent with the goals of spatial multiscale environments to rely on spatio-visual perception for "maintaining an intuitive sense of location and of relationship between information[lx] objects" [21, p. 23] and so should match user expectations.

Principle 6 Discontinuities in Plan Organization
Discontinuities in the plan organization increase the likelihood of wayfinding error.

Each of the two proposed locomotional structures uses only a single organizational principle, so neither has discontinuities due to junctions between two principles. Conceptually, the lattice structure of the Voronoi-based structure contains no discontinuities. However, if the user is not fully aware of the principle of selecting the closest zoom-in target, they may perceive discontinuities if hitherto unavailable locomotional options suddenly become available when an object reaches its maxscale. For example, in Figure 59, zoom-in past object **B** jumps from constrained no-option locomotion into a branch region with options to objects **A** and **C**.

Such "pop-up" branch regions could be eliminated either by disallowing zoom-in past the ends of objects or by introducing a requirement that a zoom-in branch region always offer a subset of the options offered by the previous branch region. The latter requirement imposes a dynamic dependency that requires monitoring branch region options as they are passed. Eliminating pop-up branch regions eliminates some of the alterative routes in the Voronoi-based structure, but does not prevent the user from reaching any destinations. Whether pop-up branch regions are a bug or a feature depends on the user's task, and the determination of whether they should be permitted must be made by the designer.

[lx] Meaning objects in the information space, not objects contributing to informational design.

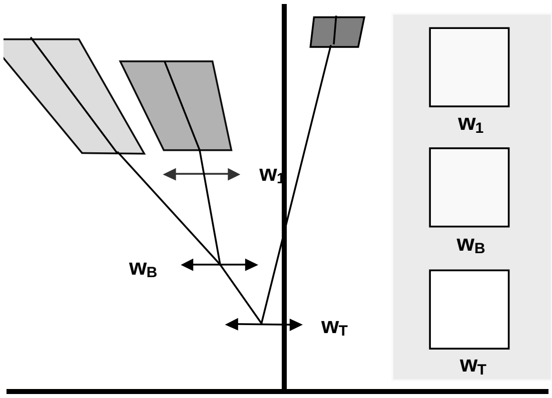


Figure 61 Relationship between information and locomotional structure.

Schematics on right show actual view contents.

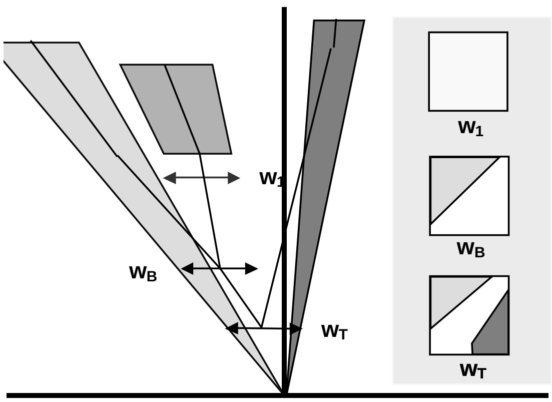


Figure 62 Relationship between information and locomotional structure if two objects have no minscale.

Schematics on right show (possible) actual view contents.

The hierarchical structure of the cluster-based design creates a tree structure that offers no such opportunities for perceived discontinuities. Each branch region naturally subtracts from (zoom-in) or adds to (zoom-out) the set of available options monotonically. Correspondingly, the region within which movement is possible contracts or expands without radical changes to locomotional options.

Principle 7 Route Complexity

The more branch regions along a route, the greater the likelihood of wayfinding error along it.

As discussed earlier (*Branch Regions Revisited*, p. 223), the cluster-based structure introduces a minimum number of branch regions and offers the shortest routes possible (given the desire to distribute options across multiple branch regions). This structure is a substructure of the lattice-structure of the Voronoi-based structure, so these shortest paths are available to users. However, the alternate paths of the Voronoi-based structure may contain more branch regions than the shortest paths. However, none of these branch regions can be eliminated without reducing the benefit of increased likelihood of wayfinding success that is introduced by the alternate paths.

Note that, because of branch region automation, the user may not need to make decisions at branch regions. As the present design makes no assumptions about informational design, it is possible that a branch region has no associated preceding or coinciding information access region. For example, the object configurations in Figure 61 and Figure 62 yield the same locomotional structure, but different information is available at the indicated branch regions. In such cases, the user may not even be aware that they are passing a branch region. If the branch region is well-automated, this can be presumed to reduce the cognitive overhead of wayfinding—not only does the user not have to make a decision, they do not even have to consider whether they might want to make a decision. Poorly-automated branch regions that have no associated information access regions, conversely, could be expected to increase the cognitive overhead even more than poorly-automated branch regions that do.

The influence of information access regions on the reflect of automated branch regions suggests an interaction between branch region visibility—a property of informational design—and branch region automation that can be formulated as a further design principle:

Hidden branch regions

- A branch region option is ***hidden*** if none of the branch region's preceding or coinciding associated information access regions provides information about the option.
- A branch region is ***hidden*** if it has no preceding or coinciding associated information access region, or if all but a single option is hidden.
- Non-hidden branch regions or branch region options are also known as ***exposed*** branch regions or branch region options, respectively.

15. Hidden Branch Regions

Hidden branch regions decrease the cognitive overhead wayfinding substantially if they are well-automated, but increase it substantially if they are not.

	Automated	Manual
Hidden	Invisible	Spectral
Exposed	Transparent	Mundane

Figure 63 Suggested nomenclature for hidden/automated branch regions and branch region options

Figure 63 suggests a nomenclature for the different ways of combining automated and hidden branch regions and branch region options. Of the four combinations, only mundane branch regions and branch region options have been explored in the psychological literature. Other combinations exist in the physical world, but are not the norm. For example, in a maze of mirrors, such as may be found in old-fashioned amusement parks, branch regions are virtually spectral and the challenge is precisely to find the branch regions. Tiger traps represent invisible branch regions that are poorly-automated from the perspective of the tiger, but well-automated from that of the hunter. In contrast, in electronic environments, it is common practice intentionally to create invisible or transparent branch region options for infrequently used options in order to facilitate selection of those that are used frequently.

Figure 64 shows an informational design for the Voronoi-based structure that converts invisible branch regions to transparent branch regions by providing feedback about the default option of upcoming branch regions. The user can change the selected option by moving the mouse before exiting the branch region.

Principle 8 Location of Information Access Regions

Information access regions must be located within the locomotional structure if they are to figure in wayfinding.

Because of the interaction between windows and the spatial multiscale environment, an object must intersect the viewing window in both planar and scale dimensions in order to be visible in a particular view. An information access region is thus guaranteed to be coincident with its associated information region. If the placement of information regions is based on the placement of data objects, the associated information access regions will be within the locomotional structure. If the information is supplied by the data object itself, this may occur naturally, as shown in Figure 62.

The user clicks on or near the object to which they want to go.

The informational design provides feedback—here a thumbnail image—about the currently selected target (the default option at upcoming branch regions).

If the selected option is incorrect, the user may select another by moving the mouse without stopping the zoom.

Zooming stops when the target is reached, if no other destinations can be reached by zoom-in.

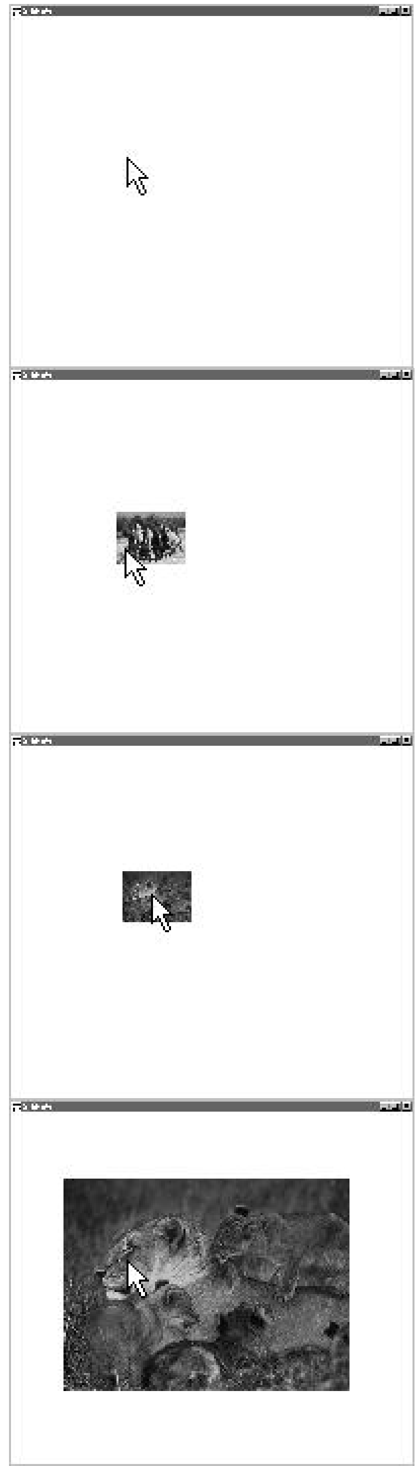


Figure 64 Conversion of invisible branch regions to transparent branch regions in Voronoi-based structure.

If the information is provided through special information objects, it may be possible to adapt the locomotional structure to include available information access regions. For instance, a fractal grid has been proposed as a means of providing orienting information in spatial multiscale [82]. The surface is subdivided by a grid, and grid lines or locations are indicated. Because of the decrease in visible surface area as the view is magnified, this grid must be successively refined with zoom-in (Figure 65). As no specific paths were defined in the task-defined structure, both mouse-proximity- and cluster-based structures are free to divert paths to pass through near-by views containing informational objects such as grid markers (Figure 66, Figure 67). Of course, large path diversions are undesirable: These not only risk increasing path lengths beyond the acceptable (from a performance perspective), but may also make the user's sense of spatial orientation unreliable. In the case of a fractal grid, large distortions are not required if the spacing between markers is less than the window size.

Principle 9 Precedence of Information Access Regions

An information access region entry port must precede or coincide with its associated branch region exit ports, if the information the information region provides is to figure in any wayfinding decisions executed at that branch region.

The present design does not make any assumptions regarding the informational design. As discussed in the previous section, it may be possible to adapt the locomotional structure to existing information access regions. If possible, this approach can ensure that included information access regions precede their associated branch regions. Although informational design is outside the scope of the present work, the reliance of both proposed locomotional designs on object layout and zoom-in branch regions suggest two simple approaches to informational design for zoom-in information. It is not clear how to provide zoom-out information, other than possibly providing You-Are-Here type inset views.

One possibility for providing zoom-in information regions is to augment the environmental information with landmark objects that indicate locations of data objects, e.g., by marking their centers (Figure 68). Such landmark objects are designed not to change size as view magnification changes, and to disappear when the object itself is reached [138]. As it is possible, in either proposed structure, for a view to contain no data

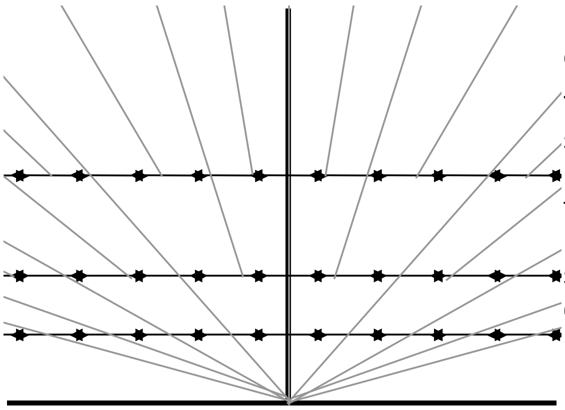


Figure 65 Fractal grid provided for orientation in multiscale.

Top-level grid markers are never faded with scale. Secondary markers appear with regular increases in magnification (here a factor of 2).
Note that developing a meaningful labeling system for grid locations is a (potentially difficult) problem in informational design.

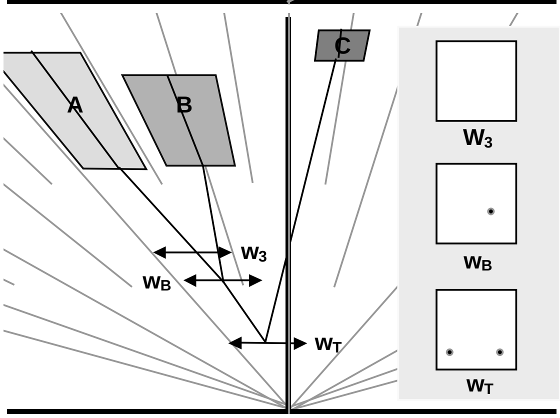


Figure 66 Cluster-based locomotional structure with fractal grid.

Schematics on right show (possible) actual views. Dots indicate locations of grid markers.

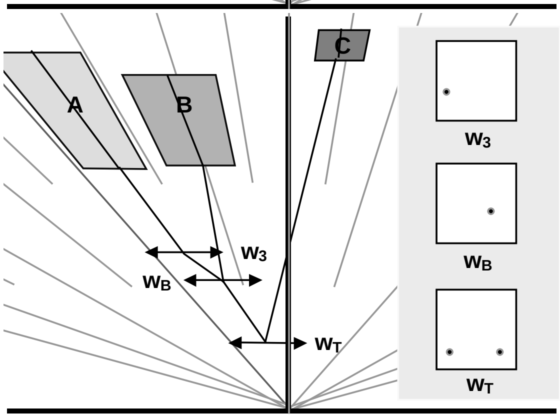


Figure 67 Cluster-based locomotional structure adjusted to include grid marker in view, if possible.

The path from $\mathbf{w_B}$ to object **B** is shifted to the left to include the nearest grid marker in views, shifting $\mathbf{w_3}$ to the left to capture primary grid marker

object, this approach does not ensure that all views contain information. However, it does guarantee that branch region views provide information about all options.

Another approach is to provide a prosthetic viewing aid that shows the "critical zones"—outlines of the populated portions of the view [138]—of the current view. In the Voronoi-based locomotional structure, the Voronoi cell boundaries are shown (schematic views in Figure 52). In the cluster-based locomotional structure, the convex hulls of object groupings at the next branch region are shown (Figure 69). This approach

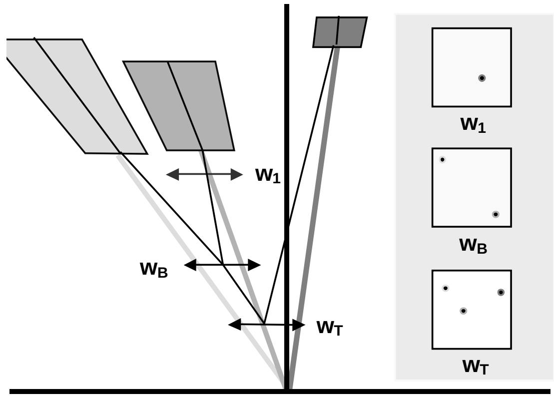


Figure 68 Environmental informational design indicating possible destinations.

Grey lines show landmarks that indicate object centers extended through scale.

Schematics on right show (possible) view contents.

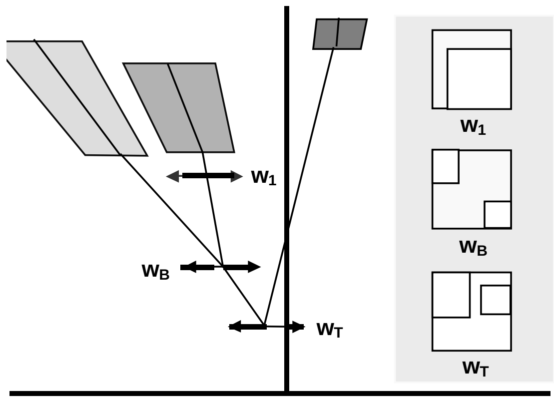


Figure 69 Prosthetic informational design indicating branch region options.

Bars indicate critical zones of views.

is computationally more intensive than providing landmarks, but guarantees that all views are information access regions.

Principle 10 Branch Region Speed

The less time—per non-viable option—allowed in a branch region, the higher the likelihood of wayfinding error.

In order to gather the full benefits of a spatial multiscale environment and a zooming user interface, movement must be continuous and visually perceptible, i.e., animated over time [**19**]. This engages the user's visual system in maintaining a sense of spatial location and offers a high degree of visual momentum (cf. Chapter 2, *Woods: Visual Momentum*, p. 84). Traditionally, if the user controls both starting and stopping of movement, speed is either held constant at a rate determined by the programmer, or is controlled by the user. If the user only controls starting movement, e.g., when movement

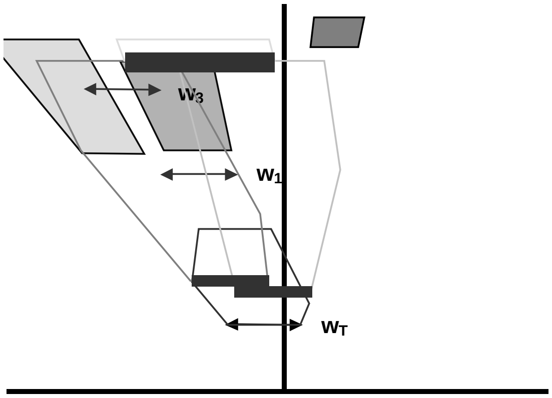


Figure 70 Branch region speed bumps placed at entry ports in Voronoi-based locomotional structure.

Speed between speed bumps may be uniform or proportional to the distance to the next speed bump or data object.

Bars show "speed bumps"—points at which speed is reduced. Width of bar indicates how long it takes to move across speed bump (how much speed is slowed).

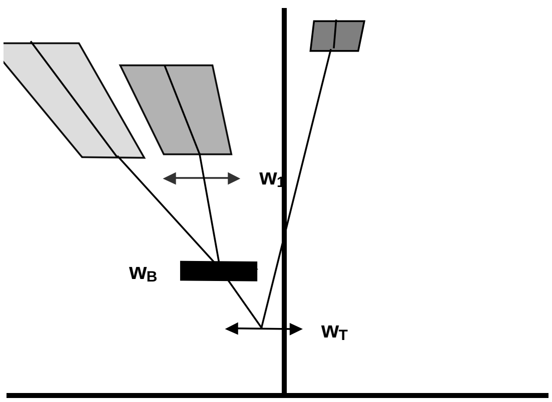


Figure 71 Branch region speed bumps in cluster-based locomotional structure (assuming automated branch regions).

Speed between branch regions can be kept constant or it can be accelerated to create a slow-in-slow-out motion effect, depending on the needs of the task.

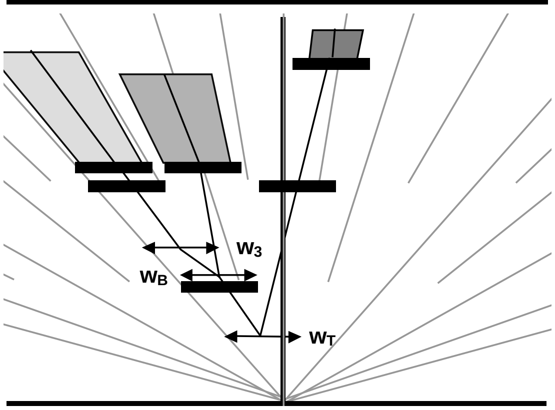


Figure 72 Information access region speed bumps in cluster-based locomotional structure (adjusted to include information access regions).

between two locations is pre-defined (hyper-linked), slow-in-slow-out motion[lxi] is generally used, at rates set by the programmer.

Regardless of whether speed is controlled by the system or by the user, it can be adjusted by introducing *speed bumps*—points at which movement is slowed automatically. (If speed is controlled by the user, such slowing would be made

[lxi] An animation technique whereby movement starts slowly, is faster in the middle and ends slowly.

proportional to their indicated desired speed.) Movement would be slowed at branch region entry ports, and the time required to move through the branch region made proportional to the number of options. Given the distance between entry and exit ports of the branch region, an average speed can be computed. Movement between branch regions can then be held constant at this average speed. Alternatively, it can be accelerated as the wayfinder has had time to consider the available options, possibly creating a slow-in-slow-out motion effect. Which of these is desirable may depend on properties of the task; in particular, they may affect the user's sense of distance differently.

In the Voronoi-based structure, branch regions have a natural extent in scale and speed bumps are easily introduced at branch region entry ports (Figure 70). Branch regions in the cluster-based locomotional structure have no extent in scale, so it is necessary either to define an area around the branch region as a de facto entry port and use that to function as a speed bump (Figure 71), or to pause movement at the actual branch region for the requisite period.

Principle 11 Information Access Region Speed

The less time—relative to the amount of information offered—allowed in an information access region, the less likely the information offered is to figure in wayfinding.

Considerations for adjusting speed of movement at information access regions are largely identical to those for adjusting speed at branch regions, and the same technique of introducing speed bumps can be used (Figure 72). There are, however, three concerns that differ. First, of course, the time needed to move through the information access region depends on the information content rather than the number of branch region options. Second, speed may affect perception differently in different modalities. For example, aural perception in the physical world is more subject to speed-induced distortion (e.g., the Doppler effect) than visual perception. Thus, modality may determine whether speed through an information access region should be kept constant or whether it may be accelerated. Third, it may not be possible to define a speed bump "region" around an information access region, and it may be necessary to pause movement altogether for the requisite period.

Increasing Wayfinding Complexity

The present design goals impose no concerns other than reducing the overhead of wayfinding as much as possible. There are, consequently, no reasons to attempt to increase wayfinding complexity.

Summary: Inter-Object Navigation Design

Consideration of the task of navigation in a spatial multiscale environment has resulted in two designs aimed at supporting the subtask of inter-object navigation. Both designs are based on the spatial layout of objects in the environment and both constrain movement always to lead toward one or more objects.

Voronoi-Based Design

The first design uses the Voronoi-based structure. It is suitable for tasks or subtasks that do not require navigation to arbitrary locations in space-scale. Zoom-out and zoom-in interactions are separated, allowing these to be controlled, for example, by using different mouse buttons. When the user clicks to zoom-out, movement is constrained always to move toward the Top of the World view (the most magnified view that contains all objects in the environment), regardless of the position of the mouse. Movement stops automatically when the Top of the World is reached.

When the user clicks to zoom-in, the system selects the object that is closest to the mouse—for example, in simple planar distance—as the current destination. It then animates viewpoint movement along a space-scale trajectory that leads to a view in which the target object is centered in the view at a reasonable magnification, for example, when the object fills 90% of the viewing window. Movement stops automatically when no object can be reached by zoom-in. If the mouse is moved so that it is closer to an object other than the current target object at any time during zooming, that object is selected as the new target destination, and a new space-scale trajectory is computed.

This Voronoi-based locomotional structure violates *Principles 2* (*Number of Branch Regions*) and *3* (*Complexity of Branch Regions*) in that its plan complexity is significantly higher than necessary, that is, it has more branch regions and its branch regions have more options than a minimal structure. However, design intuition argues that other properties of the design offset this shortcoming. Based on this intuition, a hypothesis is offered that suggests that the greater number of branch regions and branch region options is due to a proliferation of alternative routes. While the presence of these alternative routes may increase the number of decisions the wayfinder has to make, they may also reduce the number of correct decisions they must make. In other words, they reduce the consequences of “erroneous” decisions.

A second hypothesis is offered—also based on the intuition that other properties of the design are compensating for the proliferation of branch regions—that suggests that automation and hiding of branch regions may eliminate the need for the wayfinder to make some decisions or even be aware of the possibility of making a decision. This may allow the user to proceed successfully with a perceived locomotional structure that contains less complex routes than those offered by the actual locomotional structure. In other words, although the actual structure is more complex than necessary, the design does not require the user to process or even be aware of the full complexity, even along routes actually followed.

These violations are attributable to two aspects of the design that rest on decisions based on design intuition and past experience rather than direct application of the principles. The first of these is the introduction of the Top of the World. While the need for a stable location was recognized from application of the design principles, understanding and recognition of the significance of zoom-out, in general, and of the special nature of the Top of the World view was due to prior experience with space-scale interaction. The second aspect of design that rests on prior experience and design intuition is the concept of mouse-proximity steering. While the recognition that unoccupied space does not constitute a valid destination was due to application of the principles, use of the mouse to “select” the nearest object resulted from a combination of understanding conventional mouse-based interaction and experience with design of a computational environment that employs a metaphor of continuous space.

Although these two aspects of the design are the main sources of the violations of the design principles, they are most likely also the main sources of the success of the design. Although neither was due directly to the principles, the principles guided design considerations to the appropriate problems. It is interesting to note that, like the file system design, the Voronoi-based does not introduce revolutionary interaction techniques, but relies on elaborations of existing techniques. The Top of the World view is a special instance of an earlier concept of *critical zones* [137]—the area of a viewing window that actually contains information objects—that resulted from consideration of problems imposed by interaction with spatial multiscale environments. Mouse-proximity steering is a natural extension of standard mouse-based object selection and resembles other techniques proposed for constraining movement relative to objects [85, 104, 177].

The one aspect of the design that may represent more novel interaction technique and which is directly attributable to application of the design principles is the concept of speed bumps. Although others have proposed adjusting the information presented in accordance with the speed of movement [125, 263], the concept of adjusting speed to accommodate decision-making does not seem to have been proposed before.

Cluster-Based Design

The second design uses the cluster-based locomotional structure. It is suitable for tasks and layouts that are hierarchically structured or that depend on hierarchical structure. The cluster-based structure results from analysis of the spatial clustering of objects on the surface (assuming a clustering algorithm that results in a hierarchical structure). Zoom-out as well as zoom-in is constrained to follow the resulting nesting structure of object groupings.

When the user clicks to zoom in, the viewpoint is moved toward the Top of the Group of the largest group that is selected or that contains the selected object. Mouse-proximity steering may be used, but is not assumed, by this design. The designer may elect to stop movement when the Top of a Group is reached or to allow automatic option selection. When the user clicks to zoom out, the system animates viewpoint movement along a space-scale trajectory that leads toward the Top of the Group of the smallest group containing the current view, i.e., the next node up in the hierarchy.

This design is consistent with the 12 principles derived from the existing psychological evidence and was derived directly from these. It is suitable for a smaller range of design situations than the Voronoi-based design, but may, in those situations, be more effective than the Voronoi-based design.

Further Considerations

Like the Repeat File Access design, the designs for inter-object navigation in spatial multiscale address only one of three subtasks, namely that of moving between existing objects. They do not address the subtasks of moving to an unoccupied portion of space-scale (e.g., to place an object there), or the task of browsing and interacting with the space and its contents as a whole. Because of the nature of spatial multiscale environments (adding a scale dimension to a two- or three-dimensional display), a special tool, such as that developed by Furnas and Zhang [83], is required to accomplish the browsing and editing task.

While the Voronoi-based design enables locomotion to any location within the occupied portion of the world, getting to a specific unoccupied location may require awkward "jockeying" locomotion. The cluster-based design does not permit locomotion to any unoccupied locations except those that represent branch regions. Locomotion to unoccupied space can, of course, be accomplished by reverting to a conventional locomotional design.

However, it may also be accomplished through a hybrid design that, at the user's request, allows free movement within a limited area, e.g., a Voronoi cell (Voronoi-based design) or the containing group (cluster-based design). To allow the user to move to areas entirely outside the occupied portion of the surface, it might possible to allow the user, on request, to zoom out past the Top of the World. They might then either indicate areas explicitly within which they would like to be allow to move or place temporary "grapnel objects" that serve as locomotional guides and, in effect, create new Voronoi cells. "Grapnel objects" could also serve to allow locomotion to unoccupied zoom-in locations (e.g., past an End of Object).

Whether either allowing limited unrestricted freedom of movement or providing "grapnels" is, in fact, a viable design solution, of course, depends on further task analysis and both solutions are likely to require experimental prototyping both for understanding and refinement. Thy are merely offered here as possible starting points.

Predictive Targeted Movement

The design examples that were used to illustrate the application of the design principles—everyday file system interaction and multiscale navigation—seem superficially unrelated. However, as their wayfinding needs were analyzed and the designs developed, a number of similarities were revealed.

From a wayfinding perspective, the two examples exhibit four key commonalities. First, both are related to finding or searching rather than browsing, and entail movement to a particular target location with no concern for the particular path used to get there[lxii], and with a priority on getting there quickly. Second, both offer environments defining some pre-existing locomotional structure. Third, both permit computational identification of destinations and routes. Fourth, both provide a means of estimating the likelihood of a particular destination being the user's intended destination, at any given time.

These similarities resulted in designs that, although quite different in presentation (compare Figure 35, p. 181, and Figure 64, p. 230), nonetheless have enough in common that an underlying general algorithm can be identified. This algorithm represents a technique—dubbed *Predictive Targeted Movement* (PTM) [136]—for designing and supporting targeted movement. This technique is suitable when criteria for predicting the likely desirable movement can be specified.

The algorithm, shown in Figure 73, comprises four basic steps. First, (Figure 73, lines 3 – 4), the set of potential destinations are determined and displayed. Second, (Figure 73, lines 10 – 20), when movement is initiated, the set of likely destinations is predicted based on the user's input. If it is appropriate to the design situation, a means for renegotiating the prediction with the user or for allowing the user to select from the

[lxii] Note that this similarity was not observed until the actual designs started to emerge, i.e., it was not noted even during the formative task analyses.

predicted set is then engaged. Third, (Figure 73, lines 23 – 33), prediction, negotiation and selection of a route to the target destination take place. Fourth, (Figure 73, line 28) the first step necessary to moving along that route is taken. This algorithm can be incorporated into an application framework with default definitions for data types and subroutines supplied as appropriate to the environment. These default definitions can then be modified or replaced as needed for a particular application.

```
// Display possible destinations, if appropriate
possible_destinations = compute_destinations();
display_destinations();

while(      move_requested( true )
       and !target_reached( target ) ) {

 // Select target destination, negotiating selection with
 // user if appropriate
 target_set = predict_target( possible_destinations,
                               input_event );
 show_feedback_target( target_set );

 if( target_set.size() > 1 ) {
  target   = negotiate_target( target_set );

 } else {
  target   = target_set.getNext();

 }

 // Select route, negotiating selection with user if
 // appropriate
 route_set = predict_routes( target,
                              input_event );
 show_feedback_route( route_set );

 if( route_set.size() > 1 ) {
  route   = negotiate_route( route_set );

 } else {
  route   = route_set.getNext();

 }

 // Move one step along selected route
 move_increment( route );
}
```

Figure 73 Predictive Targeted Movement (PTM) algorithm

For instance, in the file system interaction design, destinations are defined as files or folders shown in windows, and routes as sequences of hyperlinks. User input identifies the desired target uniquely, so `show_feedback_target` can return without performing any actions. In this design, each route comprises only one step, so there will only be a single iteration of the `while` loop.

In the multiscale navigation design, destinations are defined as views of objects and routes are space-scale trajectories. No special actions are needed to compute and display the possible set of locations, so `compute_destinations` and `display_destinations` can be non-operative. (They could also, for example, invoke a query mechanism and highlight the result set.) If mouse-proximity steering is based on simple planar distance, the target is determined uniquely (in most cases), so no destination or route negotiation is needed. However, it could easily be imagined that distance could be augmented with a weighting system, based, for example, on relevancy of individual items in the query result set. This might require negotiation of either destination or route.

Not surprisingly (given its origins), the PTM algorithm bears a close resemblance to wayfinding problem-solving and decision-making. The primitives used by the algorithm correspond to the cognitive concepts of destination and route. Development of a mental representation is supplanted by development of a situation presentation. Route-prediction is converted to destination-prediction and route-calculation. Route-selection and route-following are identical.

The significance of PTM lie not only in its general applicability, but also in the evidence it provides that embedding the constraints represented by the identified design principles into application frameworks may be a viable means of communicating them to designers and developers. Further, it illustrates how high-level cognitive considerations may affect and be addressed through low-level design.

#	Name	Principle	Page
1	**Locations and Paths**	The locations and paths offered by the locomotional structure must be a superset of the destinations and routes in the task-defined structure.	169
2	**Number of Branch Regions**	Increasing the number of branch regions in the locomotional structure is likely to increase wayfinding difficulty, and decreasing the number is likely to decrease difficulty.	175
3	**Complexity of Branch Regions**	The fewer options offered in a branch region, the simpler the wayfinding will be.	176
4	**Task Logic and Organizing Principle**	The more closely the logic of the organizing principle of the locomotional structure corresponds to the logic of the task, the less overhead is introduced by wayfinding cognition.	178
5	**Simplicity of Organizing Principle**	Within the organizing principles made possible by the task, the simpler the principle, the simpler the wayfinding	183
6	**Discontinuities in Plan Organization**	Discontinuities in the plan organization increase the likelihood of wayfinding error.	184
7	**Route Complexity**	The more branch regions along a route, the greater the likelihood of wayfinding error along it.	185
8	**Location of Information Access Regions**	Information access regions must be located within the locomotional structure if they are to figure in wayfinding.	186
9	**Precedence of Information Access Regions**	An information access region entry port must precede or coincide with its associated branch region exit ports, if the information the information region provides is to figure in any wayfinding decisions executed at that branch region.	187
11	**Information Access Region Speed**	The less time—relative to the amount of information offered—allowed in an information access region, the less likely the information offered is to figure in wayfinding.	189
12	**Steering and Locomotional Structure**	The fewer or less precise steering actions that are required to follow the selected route and to remain within the locomotional structure, the fewer wayfinding errors are likely.	190
13	***Automated branch regions***	*An automated branch region decreases the difficulty of wayfinding if it is well-automated, but increases the difficulty if it is poorly-automated.*	*222*
14	***Alternative Routes***	*Alternative routes to destinations may decrease wayfinding performance, but increase the likelihood of wayfinding success, particularly if they are clustered around the optimal route.*	*227*
15	***Hidden Branch Regions***	*Hidden branch regions decrease the cognitive overhead wayfinding substantially if they are well-automated, but increase it substantially if they are not.*	*230*

Hypothesized principles are shown in italic.

Figure 74 Complete set of design principles.

Summary

This chapter has developed a set of fifteen design principles, summarized in Figure 74. These principles focus on environmental locomotional design, although several touch on informational design. A number of principles that pertain only to informational design were omitted, in spite of being evident from the empirical evidence described. For example, the "value" of the information at an information access region—how large a role it is likely to play in problem-solving and decision-making—is affected by the number of decision points intervening between the information access region and the branch region to which the information pertains, and is inversely related to the temporal distance between the two. The derivation of such principles requires discussion of the nature of the information content offered by the design and is beyond the scope of the present work.

This chapter also presented two examples of the application of the principles to design, and offered a brief sketch of a design process that seems prescribed by satisfaction of the implied constraints. This resulted in three designs, the Repeat File Access design for everyday file system interaction in a conventional desktop environment, and the Voronoi-based and cluster-based designs for inter-object navigation in a multiscale environment. Although these designs were developed by application of the design principles, several key design decisions rested on design intuition and experience (e.g., the division of branch regions according to file type in the Repeat File Access design, the selection of the Top of the World view as a special location in the Voronoi-based design). While each of these decisions had significant consequences, none were, in themselves, radical decisions. This suggests that, although the principles did not help answer the questions that required these decisions, they may have led to asking the right questions.

The three designs appear quite different superficially, but can be shown to have significant underlying similarities. These similarities were captured in a generalized algorithm, *Predictive Targeted Movement*, which can readily be incorporated into application frameworks supporting different types of interaction environments.

The twelve initial principles were derived from the empirical evidence described in Chapter 3. They demonstrate that design knowledge can be extracted from psychological knowledge. The three additional principles were formulated to account for design intuitions that appear to contradict certain of the principles derived from psychological knowledge. These hypothesized principles suggest that design requires more information than is available from existing psychological knowledge.

In particular, psychology aims to understand how a broad range of cognitive behaviors may be affected by environmental manipulations, while design needs to understand how a broad range of environmental manipulations may affect cognitive behaviors. Design consequently requires exploration of the effects of minor environmental manipulations, whereas such studies may contribute little to psychology. Additionally, psychology often seeks to delineate different cognitive behaviors, and so must typically explore boundary cases. Design, in contrast, must account for average or typical behavior and need only deal with extreme cases in exceptional circumstances. These observations suggest that, although design can benefit from psychological knowledge, it must also be prepared to question its completeness and push for extensions.

The derivation of the principles completes the third step of the design knowledge development for understanding wayfinding as a problem in environmental locomotional design (Figure 4)—understanding the implications for design. The design examples and design process completes the fourth step—understanding the application of the implications for design. The following chapter presents an empirical study aimed at determining whether application of the principles actually helped achieve design goals.

CHAPTER 5

Empirical Evaluation

"This is called teamwork. I furnish the brains.
You furnish the muscles, the aches and the pains.
I'll pick the best roads, tell you just where to go
And we'll find a good doctor more quickly, you know."
Dr. Seuss, *I Had TROUBLE in Getting to SOLLA SOLLEW*[lxiii]

Wayfinding is a matter of "pick[ing] the best roads," and "tell[ing] you just where to go." Wayfinding success, however, is measured by whether "a good doctor" is found and whether a good doctor is found "more quickly." The purpose of understanding navigation as a problem in design, identifying design constraints and articulating design principles is, ultimately, to help end users accomplish their tasks in a manner that is consistent with their needs (as identified by the designers). Whether this purpose has been served can only be determined by actual user testing.

This chapter presents the experimental design and results for a user study of one of the designs developed in Chapter 4. The study compares use of the Voronoi-based locomotional structure—here called the *Leylines* design—to a conventional geometry-based design—here called the *Pad* design—for locomotion in spatial multiscale. While the experimental task is a directed search task, the experimental stimuli are designed to emulate an end-user finding task. In other words, although subjects lack direct knowledge of the locations of objects, the stimuli are designed so that locations may be determined directly from environmental information. Detailed materials associated with the study may be found in *APPENDIX F Experimental Questionnaire and Instructions*, p. 307,

---

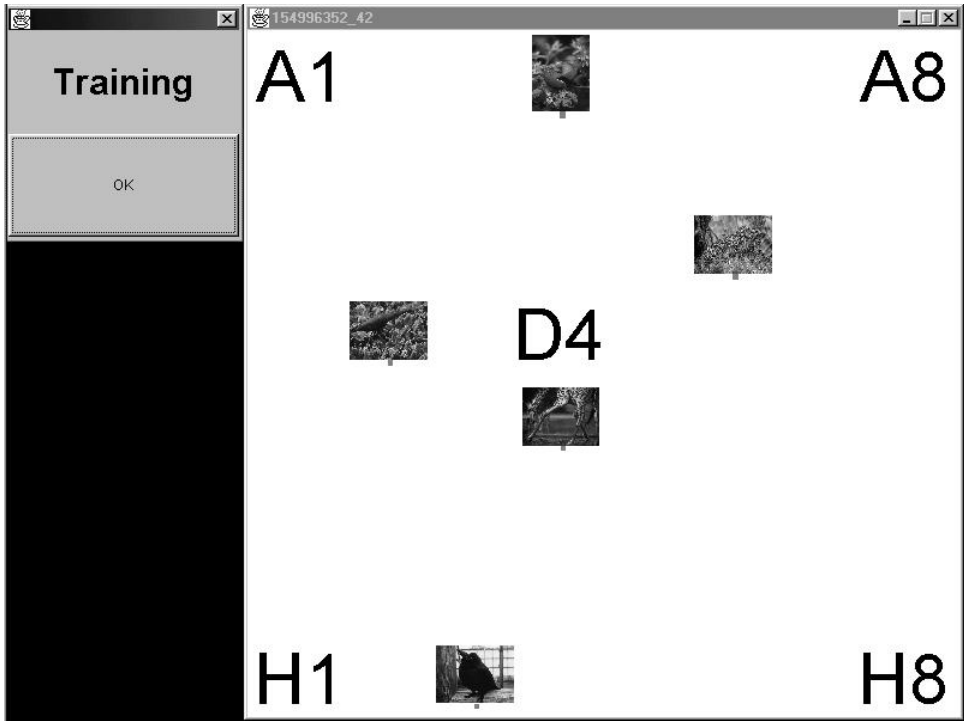
[lxiii] [240] Reprinted from *I Had TROUBLE in Getting to SOLLA SOLLEW*, Dr. Seuss, p. 21, ©1965, with permission from Random House Publications.

APPENDIX G, Subject Consent Forms, p. 329, and *APPENDIX H, Institutional Review Board Approval for Studies Involving Human Subjects*, p. 333.

The study is aimed at determining whether the manipulations suggested by the design principles, in fact, improve wayfinding performance and whether any evidence can be found that the cognitive overhead has been reduced. In order to minimize confounding factors, the Leylines design incorporates those portions of the Voronoi-based design that result from principles related to properties of the locomotional structure. This omits considerations of the relationship between locomotional structure and informational design, and between locomotional structure and movement, i.e., principles 11 and 12. The locomotional structure does thus not adapt to information access points and speed is held constant throughout, i.e., the interaction is that shown in Chapter 4, Figure 55 (p. 213).

The Voronoi-based structure was tested rather than the cluster-based structure for three reasons. First, it is the more innovative of the two designs and thus has greater potential to yield interesting results. Second, the hierarchical nature of the cluster-based structure may itself be a confounding factor, and may interact with the experimental task in unpredictable ways. Dissociating the effects of applying the principles from the effect of a hierarchical structure would entail conducting a series of experiments with varying tasks and layouts. Third, testing the Voronoi-based structure offers the opportunity to ascertain whether the properties captured in the hypothesized principles seem to be negative rather than positive factors.

The experimental results suggest that the Leylines environmental locomotional design changes the wayfinding task in fundamental ways, and reduces both physical and cognitive overhead of wayfinding. The Leylines design yielded a 30% reduction in time-on-task along with substantial and significant reductions in mouse activity both while moving and while not moving.



The locations of the photographs shown are **A4**, **C6**, **D2**, **E4** and **H3**. Subjects saw this view during training but never in testing.

Figure 75 Example layout of photographs (8 x 8 grid).

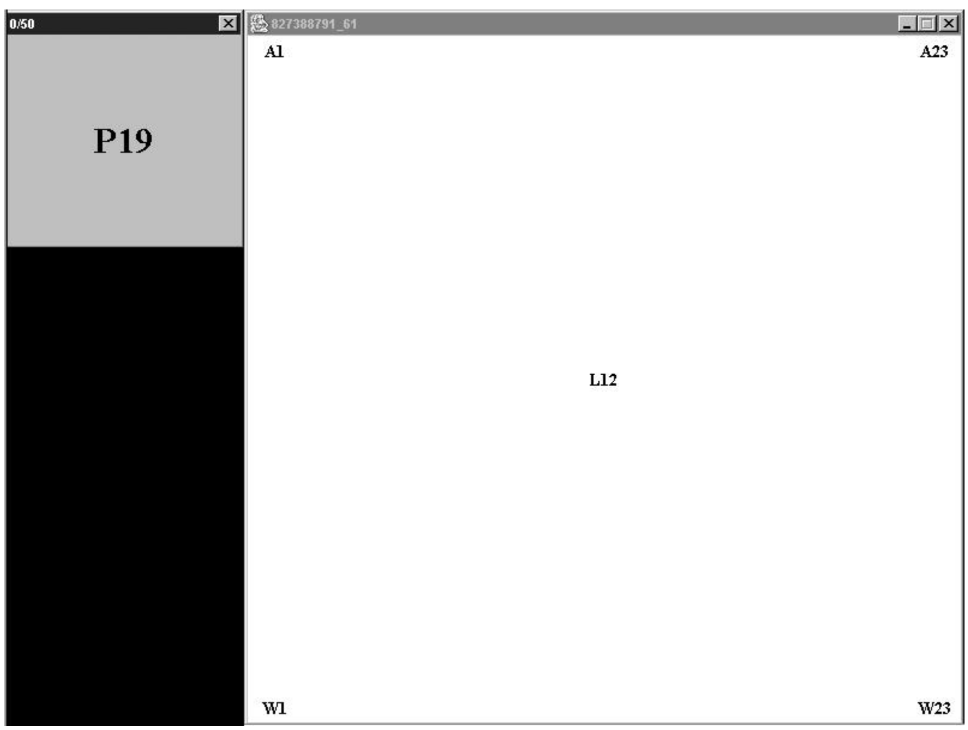


Figure 76 Top of the World view in Grid Markers experiment (23 x 23 grid).

Experimental Design

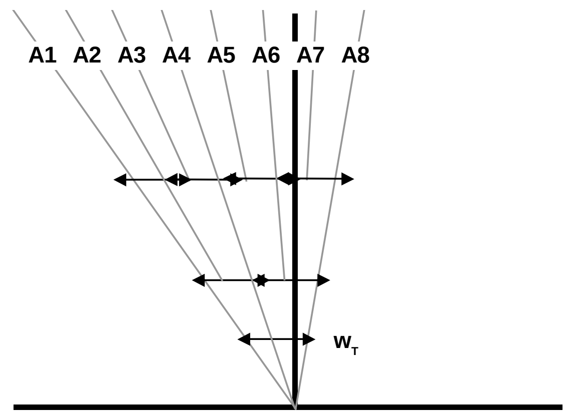
The study comprised two experiments comparing a locomotional design based on the Voronoi-based locomotional structure developed in Chapter 4 (Leylines) to a conventional geometry-based locomotional design (Pad). Each experiment employed a 1 x 2 factorial within-subject design with repeated measures. The first factor, locomotional design, was manipulated within subject—all subjects used both structures. The second factor, the order of presentation of the two designs, was varied between subjects. The two experiments differed only in the environmental informational design; the experimental tasks and locomotional designs were identical.

In the *Grid Markers* experiment, some environmental information was always available. This experiment was designed to simulate a finding task in which the user's destination is not in the view. That is, the user "knows" approximately where the destination is and the environment offers enough information for them to get there. This emulates a normal situation in much interaction, for example, getting to a file from the desktop in one's personal file system, or getting to a particular page in a website.

In the *Desert Fog* experiment, no environmental information was provided, except for labels marking destination objects. This experiment was not intended to simulate a realistic task, but tested the supposition that environmental locomotional design can alter the demands of wayfinding so dramatically that an impossible task is made possible. "Desert fog" is a condition in which no information is available upon which wayfinding decisions can be based [138]. It is inherent to certain types of environments, including spatial multiscale, and is a recognized problem in Jazz. A realistic design would take steps to prevent it from occurring, e.g., by imposing one of the informational designs outlined in Chapter 4.

Subjects

25 subjects participated in the study, all volunteering in response to broadcast email. All were students or staff at the University of Michigan in disciplines ranging from music to computer science. 9 subjects were female, 15 were male, all between the ages of



Top-level grid markers (**A1**, **A4**, **A8**) are always visible. Secondary markers (**A2**, **A6**, **A3**, **A5**, **A7**) appear with each 1.75 increase in magnification.

Figure 77 Grid coordinate markers for grid with 8 columns.

18 and 50. All subjects reported at least one year of experience with mouse-based computers (only one less than three years) and average daily computer use of at least one hour. None reported prior familiarity with zooming user interfaces. Each subject participated in a single 1.5 – 2 hour session and was compensated with a $25 gift certificate.

Stimuli

The experimental stimuli are shown in Figure 75. Two fixed-size windows display the experimental cues and the Jazz interaction environment—small and large windows, respectively. The interaction environment consists of a set of photographs laid out on the surface. Photographs are selected randomly from a collection of professional photographs [191]; 50 in the Grid Markers experiment, 6 in Desert Fog.

Photographs all have the same size and aspect ratio, but may be in either portrait or landscape orientation. Their visibility parameters are configured so that a photograph is not visible until the view magnification is such that it covers at least 190 pixels along one dimension. This ensured that it was necessary to make wayfinding decisions with no photographs in the view, and that there was time to make such decisions while moving.

Photographs all reach the visibility threshold at the same magnification and are spatially distributed to prevent visual occlusion (Figure 75).

The selection of photographs and their layout is random and generated uniquely for each training or testing run. Photographs are positioned relative to a conceptual grid. The grid is sized so that at most 10% of the cells will be occupied; a 23 x 23 grid in the Grid Markers experiment (50 photographs) and an 8 x 8 grid in Desert Fog (6 photographs). Photographs are placed in grid cells randomly with at most one per cell. Cells are slightly larger than the largest dimension of photographs. This approach to laying out the photographs guarantees that there is no overlap in either planar or scale dimensions, and ensures that the Voronoi-based locomotional structure contains no “pop-up” branch points (p. 225).

Informational Design

The informational design imposes an alphanumeric coordinate system on the grid used during layout generation. Rows are designated numerically, columns alphabetically (Figure 75). Each photograph, in both experiments, is labeled with its grid address (Figure 78, Figure 79). In the Desert Fog experiment, this is the only source of environmental information (Figure 79), however, subjects were informed (and reminded) that each training or testing run starts at the Top of the World.

In the Grid Markers experiment, the addresses of selected reference locations are displayed on the surface. These grid markers are configured as suggested by the fractal grid design discussed in Chapter 4 with secondary markers appearing at regular intervals in scale. Primary markers indicating the four corners and the approximate center of the grid (Figure 75, Figure 76) are always visible (although they may not be contained in a given view, Figure 78). Secondary markers appear with each 1.75 increase in view magnification, ensuring that views contain at least one marker (Figure 77). Grid markers are fixed in size and do not change with view magnification.

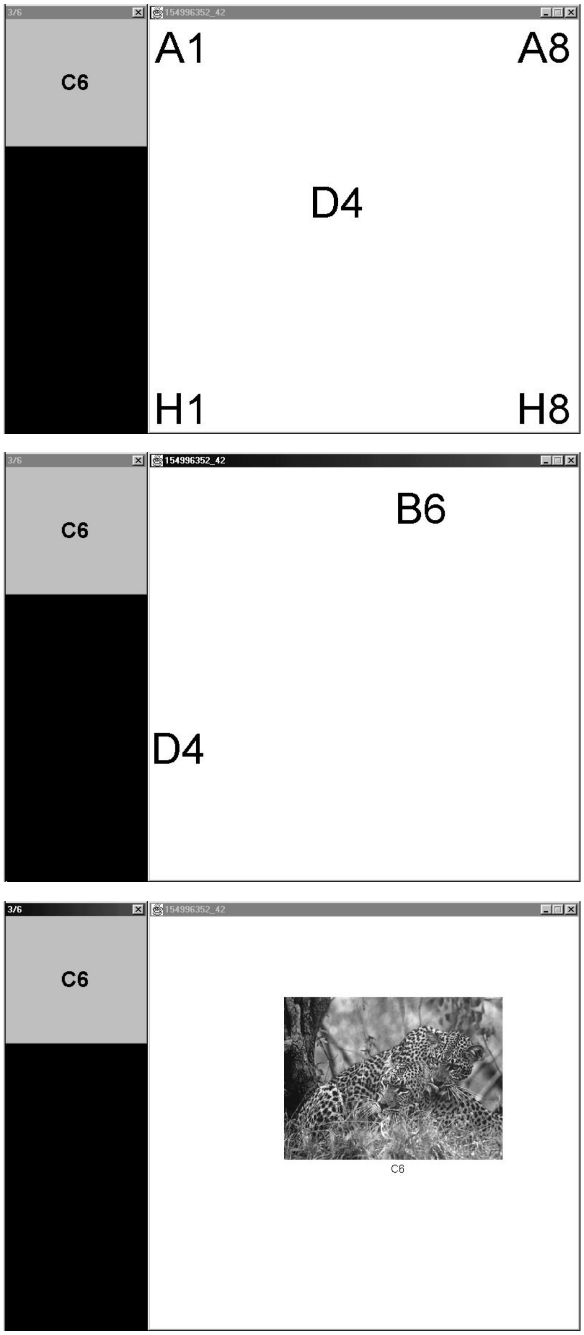


Figure 78 Grid Markers experiment.

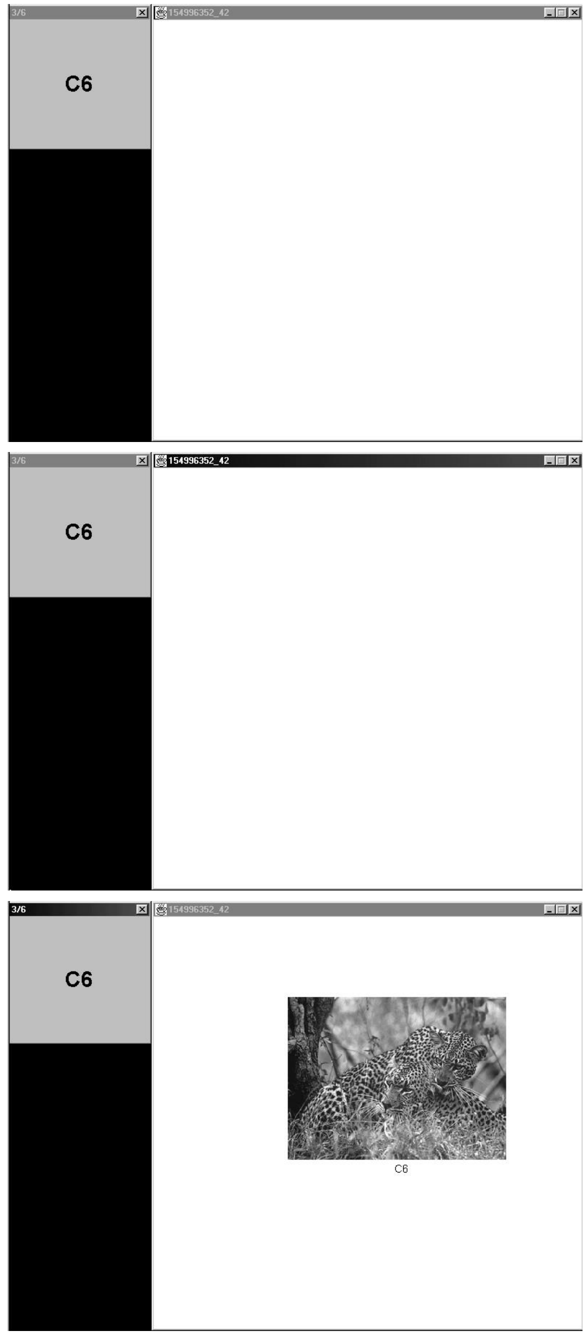


Figure 79 Desert Fog experiment.

The large window is the multiscale interaction space. The small window presents the experimental stimuli (a destination, here, ***C6****). Views show corresponding views in the Grid Markers (small layout; 8 x 8 grid) and Desert Fog experiments.*

Top: Top of the World view.

Center: Intermediate branch point view during zoom-in zoomed toward **C6**. Note the appearance of a secondary grid marker (**B6**) in the Grid Markers view.

Bottom: Destination view. Note grid location label underneath photograph.

Figure 78 – Figure 79 Experimental stimuli.

Task

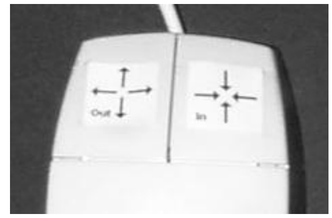
The experimental task is to move from one photograph to another. A random sequence of locations of photographs is selected without replacement, and presented, one at a time, to the subject (Figure 78, Figure 79, small windows). Subjects move to the indicated destination and press the space bar to indicate that they have arrived. If they are not at the correct location, their response is not accepted and they must continue to the correct location. If they are at the correct location, the next location cue is presented, and the subject seeks to go there from the present location. Subjects perform 15 and 5 trials (moving from one photograph to another) in the Grid Markers and Desert Fog experiments, respectively.

Locomotional Designs

The two locomotional designs are the *Leylines* design and the *Pad* design. The Leylines design is based on the Voronoi-based structure developed in Chapter 4. It uses the Voronoi-based locomotional structure design with automated branch points as described in Chapter 4, but does not adapt to information access points or adjust speed at decision points. Discontinuities in the locomotional structure are precluded by the manner in which photographs are laid out on the surface. The Pad design uses the conventional locomotional structure defined by space-scale geometry, i.e., the interaction shown in Chapter 4, Figure 41 and Figure 42. In the experiment, panning is permitted in the Pad design, but not in the Leylines design. Note that the Pad design is the locomotional design offered by Pad++ [20], the precursor to Jazz.

Steering Design

A two-button mouse was used to control movement throughout the study. The same steering design was used with both locomotional designs. The left and right buttons control zoom-out and zoom-in, respectively. Mouse buttons were labeled to reduce possible confusion (Figure 80). In the Pad model, pressing the alt key (located symmetrically on either side of the space bar, Figure 82) and dragging with either mouse



Left button zooms out, right zooms in.

Figure 80 Mouse button labeling.

Labels on edges of screen are reminders of grid coordinate axes.

Figure 81 Physical configuration.

Alt keys and space bar are highlighted with purple tape.

Figure 82 Keyboard labeling.

Figure 80 – Figure 82 Physical configuration and labeling of experimental hardware.

button pressed resulted in panning. Alt keys and space bar were highlighted on the keyboard to prevent any need to search for them (Figure 82). Feedback regarding status of movement is provided in both experiments through an animated cursor that suggests direction of zooming while zooming is in progress. If movement is blocked (Leylines design), the cursor changes to the universal “no” cursor (a circle with a slash through the center). A “hand” cursor indicates panning movement (Pad design).

Computational Environment

The study was conducted on a laptop computer with a Pentium II 266 MHz processor and 96 MB memory, running Windows 98, Java 1.3.1 and Jazz 1.0. The laptop’s 12.1” display panel was used at a resolution of 800x600 pixels. The laptop’s touch pad and mouse buttons were covered and an ambidextrous external mouse was used in their place (Figure 80).

Procedure

The two experiments were interleaved so that a subject performed both experiments with one locomotional design before repeating them with the other. Performing the task in Desert Fog conditions requires full comprehension of the locomotional design, so the Grid Markers condition preceded the Desert Fog condition. Subjects were alternately assigned to start with one or the other locomotional design to counter-balance possible order effects.

All training and instructions were given by video and on-screen messages (cf. *APPENDIX F Experimental Questionnaire and Instructions*, p. 307). An experimenter was present to answer subjects' questions during practice but not during testing sessions. Subjects received an introduction to the concepts of multiscale, zooming user interfaces, Jazz, and the experimental task before actively using either locomotional design.

After the introduction, they learned the first locomotional design to which they had been assigned, and practiced using it in a sequence of Grid Markers environments. First, they practiced with a small layout containing six photographs that were always visible (Figure 75). This allowed them to observe the behavior peculiar to that design. They then practiced on another small layout with normal visibility of photographs (Figure 78), and, finally, on a large layout, containing fifty photographs, like that used in testing in the Grid Markers experiment. Subjects were encouraged to practice as long as they liked, but were required to continue until they had moved to five consecutive targets without error (reaching an incorrect photograph) or appreciable hesitation.

After becoming familiar with the locomotional design, subjects were given tips on using it more effectively, e.g., moving the mouse during zoom-out to anticipate zoom-in. (Note that, by this point, most subjects had already discovered these techniques.) They then performed a final practice session on a large layout, and the Grid Markers test was administered. The Desert Fog experiment was then introduced and, after a single practice session, the Desert Fog test administered. Following a ten-minute break, the training and testing sequence was repeated using the second design to which they were assigned.

Data Collection

In addition to demographic and other individual information collected from each subject, a standard mental paper-folding test of spatial ability was administered. Behavioral data were recorded during their interaction with the software. Data collected included the time spent on each trial—from the presentation of the location cue until the subject presses the space bar with that location in the view—and the number of response errors (i.e., spacebar pressed when the target is not in the view). View and mouse locations were sampled and recorded approximately every 100 ms. (A sampling rather than an event-driven data collection strategy was used to avoid introducing different computational costs of data collection caused by variations in event frequencies between the two locomotional designs.)

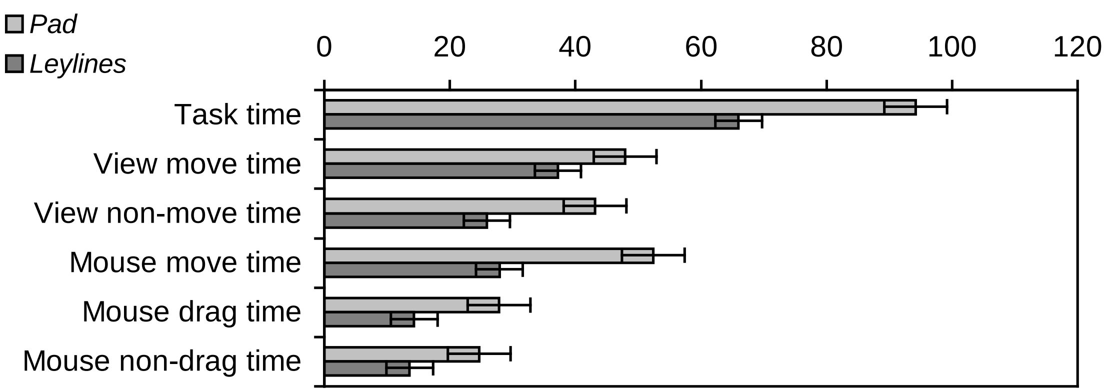
Computational Note

It should be noted that while the zoom rate—the change in magnification with each zoom increment—is constant and identical for both locomotional designs, the computational overhead of zooming is somewhat greater in the Leylines design. The mouse position is sampled every 20 ms during zooming and changes trigger a system response. In the Leylines design, this causes the underlying PTM algorithm (cf. Chapter 4, *Predictive Targeted Movement*, p. 240) to be executed. The PTM implementation was not optimized and an O(n) algorithm was used for target selection. (An $O(\sqrt{n})$ algorithm could be achieved by preprocessing the spatial layout of objects.) In the Pad design, a change in the mouse position merely causes a single translation of an affine transform.

Results

Data from one subject have been eliminated due to faulty equipment (discovered immediately following the session). Of the remaining subjects, 12 started with the Leylines design, and 12 with the Pad design. Because the experiments each have only two conditions and Leylines is predicted to be superior, paired one-tailed t-tests are used.

	Pad	Leylines	%	t(23)	p <
Time on task	94.2	66.0	-29.9	4.93	.0001
View move time (mouse press)	47.9	37.2	-22.3	3.12	.005
View non-move time	43.1	25.9	-40.0	6.24	.0001
Mouse move time	52.4	27.9	-46.8	7.08	.0001
Mouse drag time	27.8	14.3	-54.4	5.22	.0001
Mouse non-drag time	24.7	13.6	-44.9	7.61	.0001



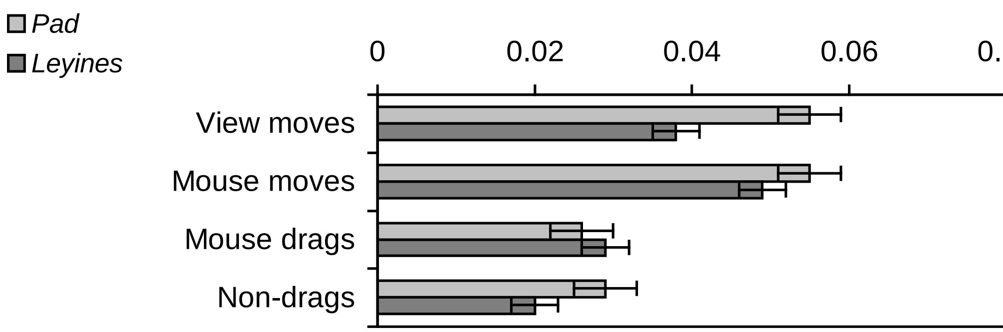
Measures are normalized to one net surface unit traveled. % column shows change from Pad to Leylines.

Table 4 Mean times on task or subtask per surface unit traveled in Grid Markers experiment (milliseconds/surface unit).

Grid Markers Experiment

In order to understand the effects of environmental locomotional design on task performance, physical effort and cognitive effort, the data are analyzed in terms of response error, time on task(s), mouse activity, and relative use of time. Because of the randomness of the layouts and target sequences, certain measures of time and mouse activity are normalized to net planar distance traveled, that is, the total planar distance between targets in a given target sequence. This distance is proportional to the length of the shortest paths through space-scale. Planar distance is measured in surface units, which, at the canonical magnification of 1, correspond to pixels.

	Pad	Leylines	%	t(23)	p <
View moves (clicks) (clicks/surface unit)	.055	.038	-30.9	4.72	.0001
Mouse moves (moves/surface unit)	.055	.049	-11.0	1.23	.25
Mouse drags (drags/surface unit)	.026	.029	11.5	1.21	.25
Mouse non-drags (non-drags/surface unit)	.029	.020	-31.0	3.47	.005



Regular type indicates values that are not statistically significant.

Table 5 Mean number of mouse actions per surface unit traveled in Grid Markers experiment.

Response Error

There was no significant difference in the number of times subjects pressed the space bar erroneously, t(23) = .24, p < .6.

Time

The results for time spent on various tasks are shown in Table 4. All but three subjects were faster overall in the Leylines design, moving the same distance in 30% less time (*time on task*), t(23) = 4.93, p < .0001. They also spent less time moving the view (*view move time*), 22% less in Leylines than in Pad, t(23) = 3.12, p < .005, as well as 40% less time not moving the view (*view non-move time*), t(23) = 6.24, p < .0001.

Subjects spent less time moving the mouse (*mouse move time*) in Leylines, 47% less than in Pad, t(23) = 7.08, p < .0001. Examined more closely, mouse move time is

	Pad	Leylines	%	t(23)	p <
View move (mouse press)	877.6	1007.1	14.8	2.83	.01
Mouse drag	1126.6	474.5	-57.9	6.00	.0001
Mouse non-drag	932.5	679.2	27.2	5.62	.0001

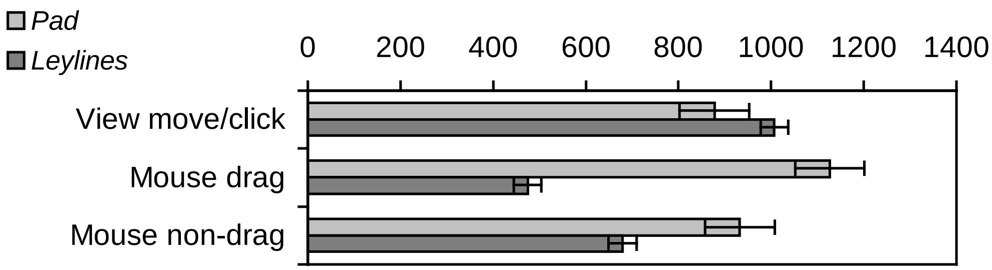


Table 6 Mean durations of mouse actions in Grid Markers experiment. (milliseconds).

	Pad	Leylines	%	t(23)	p <
Mouse drag	474.5	75.8	-84.0	5.26	.0001
Mouse non-drag	276.3	135.5	-51.0	5.31	.0001

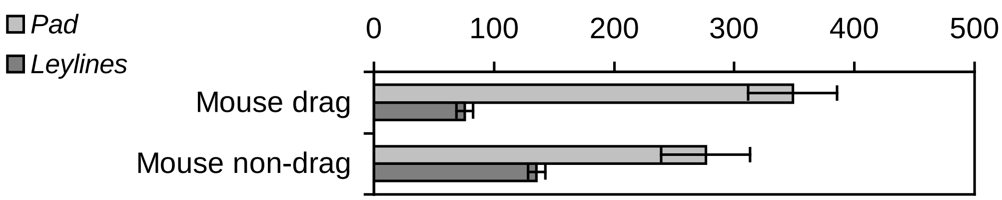


Table 7 Mean distances of mouse movement in Grid Markers experiment. (pixels).

divided into *drag* and *non-drag* time, time spent moving the mouse with and without a button pressed, respectively. Both were smaller in the Leylines condition. Drag time was 49% less, t(23) = 5.22, p < .0001, and non-drag time 45% less, t(23) = 7.61, p < .0001. (Note that total mouse drag time is a subset of total view move time as the view always moves when a mouse button is pressed, regardless of whether the mouse is moving.)

In short, overall time on task and analyzed subtasks was significantly reduced by the Leylines design.

Mouse Activity

Mouse activity is an indicator of the physical effort expended. It is measured in terms of number of mouse actions (button presses and mouse moves), duration (in time) of actions, and distance of mouse movement. Note that a *view move* is synonymous with a mouse button press. A *mouse move* is a sequence of mouse position samplings in which the position changes at least every 150 ms. (This threshold is necessary to eliminate false "stops" introduced by computational delays, e.g., for garbage collection, and was determined empirically by experimentation with mouse sampling software.)

The results for the number of mouse actions are shown in Table 5. Subjects moved the view (pressed a mouse button) 31% fewer times per unit traveled in Leylines, $t(23) = 4.72$, $p < .0001$. They also moved the mouse 10% fewer times, but this was not statistically significant, $t(23) = 1.23$, $p < .25$. Examined more closely, mouse moves are divided into *drags* and *non-drags*, mouse movement with and without a button pressed, respectively. (Mouse drags are, of course, a subset of view moves.) Subjects dragged the mouse 12% more times in Leylines, although this was not statistically significant, $t(23) = 1.21$, $p < .25$. They non-dragged the mouse 30% fewer times in Leylines, $t(23) = 3.47$, $p < .005$.

The results for durations and distances of mouse actions are shown in Table 6 and Table 7, respectively. Each view move (mouse press), on average, lasted 15% longer in Leylines, $t(23) = 2.83$, $p < .01$. The average mouse drag was 58% shorter in time in Leylines, $t(23) = 6$, $p < .0001$, and 78% shorter in distance, $t(23) = 5.26$, $p < .0001$. The average mouse non-drag was 27% shorter in time in Leylines, $t(23) = 5.62$, $p < .0001$, and 51% shorter in distance, $t(23) = 5.31$, $p < .0001$. Note the crossover in duration of view and mouse drag movement: In Leylines, mean duration of view moves was greater than mean duration of mouse moves (1007.1 and 474.5 ms, respectively). The inverse was true in Pad (877.6 and 1126.6 ms, respectively).

In short, when in the Leylines design, subjects moved the view (pressed a mouse button) fewer times, but each move was longer in time. The number of times they moved the mouse was not significantly different. The number of times they moved the mouse with a button pressed (i.e., while the view was moving) was also not significantly

	Pad	Leylines	%	t(23)	p <
View non-move time/ Time on task	.49	.42	-14.3	3.89	.001
Mouse move time /Time on task	.57	.43	-24.6	6.84	.0001
Mouse drag time/ Mouse move time	.52	.50	-3.8	.53	.6
Mouse drag time/ View move time	.58	.38	-34.5	7.24	.0001
Mouse non-drag time/ View non-move time	.56	.48	-9.0	3.62	.005

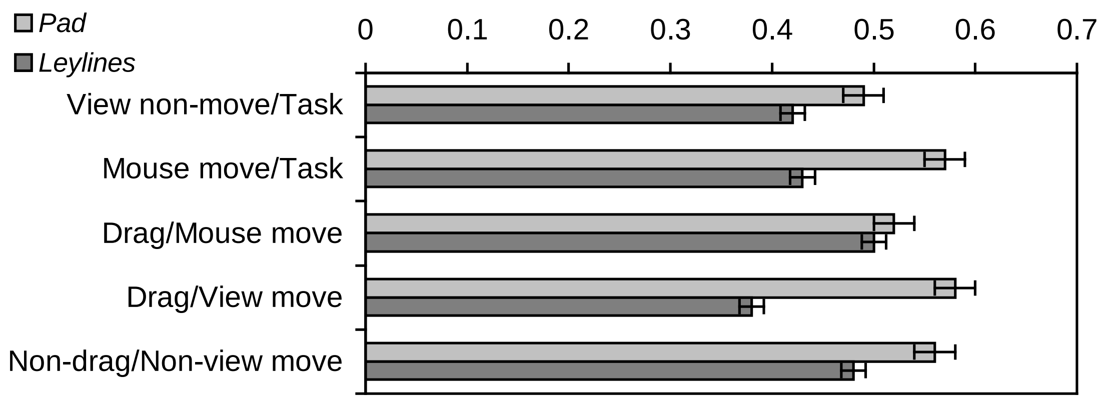


Table 8 Proportion of time on task spent on subtasks.

different, but each move was substantially shorter in both duration and distance. When a mouse button was not pressed (i.e., the view was stationary), subjects moved the mouse less often and moves were shorter in both duration and distance. The crossover shows that view moves without moving the mouse were commonly longer than combined view and mouse moves in Leylines, but shorter in Pad.

Relative Use of Time on Subtasks

In order to examine whether and how cognition was affected, the distribution of time on subtasks is examined. This analysis reveals whether the locomotional design affected how subjects used their time. It examines the following relationships: distribution of view and mouse movement within the overall task, distribution of mouse movement subtasks within overall mouse movement, and distribution of mouse movement subtasks within view movement subtasks. These results are shown in Table 8.

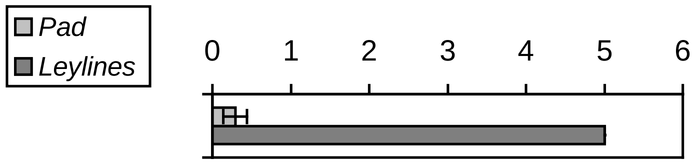


Figure 83 Mean number of trials (out of 5) completed in the Desert Fog condition. t(23) = 31.57, p = 0.

In Leylines, subjects spent 42% of the overall task time looking at a stationary view, whereas they spent 49% of their time doing so in Pad, $t(23) = 3.89$, $p < .001$. They spent 43% of the overall time moving the mouse in Leylines, but 57% doing so in Pad, $t(23) = 6.84$, $p < .0001$.

Distribution of mouse movement subtasks was approximately equal in both models, with subjects spending 50% and 52% of the total mouse move time in dragging with Leylines and Pad, respectively, $t(23) = .53$, $p < .6$.

While moving the view, subjects spent 38% of the time also moving the mouse (dragging) in Leylines, and 58% doing so in Pad, $t(23) = 7.24$, $p < .0001$. While the view was stationary, subjects spent 48% of their time moving the mouse (non-dragging) in Leylines and 56% doing so in Pad, $t(23) = 3.62$, $p < .005$.

In short, in the Leylines design, subjects spent a smaller percentage of the total time looking at a stationary view and a smaller percentage of total time moving the mouse. They also spent a smaller percentage of time moving the mouse while moving the view and while looking at a stationary view. There was no significant difference in the proportion of time spent dragging and not dragging the mouse (disregarding whether the view was also moving).

Desert Fog Experiment

The only data analyzed in the Desert Fog experiment were trial completions. With the Leylines design, all subjects completed all five trials successfully. No subject was able to complete all trials using the Pad design, giving up (discontinuing the run) after an average of .29 trials, $t(23) = 31.57$, $p = 0$ (Figure 83).

Qualitative Results

In a post-test questionnaire (cf. *APPENDIX F Experimental Questionnaire and Instructions*, p. 307), subjects reported greater satisfaction with the Leylines design. 16 of the 24 subjects stated that they preferred or strongly preferred Leylines, in general. When asked which design they would prefer to use if they "were doing something else while [they] were performing this task—say talking on the phone," 21 subjects favored Leylines. 19 subjects found Leylines easier or much easier to use, while 3 thought Pad was easier, and 2 subjects thought they were about the same.

Many subjects cited the ability to return to the Top of the World and the reduced need for accurate mouse control as particularly attractive features of Leylines. Many cited the ability to pan as a positive feature of the Pad model and the lack thereof a defect of Leylines.

Discussion

Results of the Grid Markers experiment show that the Leylines design improved task performance as measured by time, without increasing error. At the same time, the physical effort required to perform the task was reduced, as shown by the reductions in number and magnitude of mouse actions—in both duration and distance. These results are straightforward.

Other results are subtler. Subjects spent less total time, in the Leylines design, looking at stationary views, implying that less time was dedicated solely to wayfinding problem-solving and decision-making. That they also spent a smaller percentage of their time looking at stationary views could have one of two causes. Either subjects were able to solve problems and make decisions faster or they were able to do problem-solving and decision-making while moving (i.e., that problem-solving and decision-making and decision-execution had more overlap).

The latter could result from the transfer of cognitive resources from the steering task to the wayfinding task. Note that view move time is reduced from 47.9 to 37.2 ms/surface unit (Table 4), a reduction of 10.7 ms/surface unit. If it is assumed that all of this time is due to reduction in steering cognition, it “frees” 10.7 ms/surface unit of cognitive “processing” resources. If it is assumed that wayfinding problem-solving and decision-making can take place in parallel with steering cognition (as indicated by the model of navigation as a cognitive task developed in Chapter 2), these freed resources could result in a corresponding reduction in non-view move time.

However, non-view move time is reduced from 43.1 to 25.9 ms/surface unit (Table 4), a reduction of 17.2 ms/surface unit. This leaves 6.5 ms/surface unit that are not accounted for by transfer of resources. It is possible that the additional reduction is, at least in part, due to reduced cognitive effort of wayfinding problem-solving and decision-making. This is substantiated by qualitative and anecdotal evidence that subjects found Leylines “a *lot* easier!”

The decreased mouse activity when not moving indicates that subjects were less confused or less agitated when using the Leylines design. Anecdotal evidence including explicit comments about being lost or confused, and observed patterns of non-drag mouse movement (tracing out grid references and agitated “doodling”) supports the supposition that users were more confused with the Pad design and that this was, at least in part, due to spatial disorientation.

That users felt better spatially oriented during movement with the Leylines design is affirmed by the fewer but longer view moves. These suggest that users had more confidence in their wayfinding solutions and required less “stop and go” movement to review or adjust them. Interestingly, subjects used less time to move the same distance (recall that zoom speed was constant), indicating that they were following closer-to-optimal paths, despite devoting less time solely to wayfinding problem-solving and decision-making.

Results from the Desert Fog experiment show that the Leylines design changes the wayfinding task fundamentally. All subjects eventually lost spatial orientation. However, many were unable to locate even the first target in Pad, although they were aware they started at the Top of the World. This suggests that Leylines reduced the need for maintaining spatial orientation. Thus, the decrease in experienced disorientation in the

Grid Markers experiment may have been due to decreased need for rather than improved maintenance of spatial orientation.

Conclusions

The study reported here comprised two experiments comparing two different locomotional designs: one resulting from the application of the principles developed in Chapter 4 (Leylines) and a conventional design (Pad). The two experiments differ only in the informational design and size of the environment. The results show that the design informed by the design principles increased performance and reduced physical effort. They also suggest that the design probably also reduced cognitive effort. This demonstrates, conclusively, that manipulating the environmental locomotional design can change the wayfinding task—even to the extent that it becomes impossible—for all practical purposes. While the effect of manipulating environmental locomotional design may diminish as informational design improves, eliminating any superfluous cognitive overhead can only help users, particularly as the cognitive complexity of the superordinate task increases.

The study itself does not present conclusive evidence that the observed effects were due to the application of the design principles, but only demonstrates that their application does no harm and probably does some good. Evidence that application of the principles consistently produces the desired results would have to be obtained from extensive analysis of the behavioral data—demonstrating, for example, that users were, in fact, making fewer erroneous decisions—and from repeated application to a variety of design situations. Both approaches are planned for the future.

CHAPTER 6

Conclusions

I led him around and I tried hard to show
There are things beyond Z that most people don't know.
I took him past Zebra. As far as I could
And I think, perhaps, maybe I did him some good...
Dr. Seuss, *ON BEYOND ZEBRA!*[lxiv]

Brains, feet, shoes, heads, muscles, aches, pains. Mind-maker-uppers, choices, directions, steering, left, right, right-and-three-quarters (or, maybe, not quite), thinking low, thinking high, find a good doctor. Design, design constraints, problem-solving and decision-making, wayfinding, navigational design, environmental design, locomotional design, locomotional structure, task-defined structure, destinations, routes, locations, paths, branch points, branch regions, branch region entry ports.

The goal of developing a systematic understanding of navigation as a problem in design has led from brains to branch points to branch regions (and beyond). The existing alphabet, "what people already know," took the form of theories of design and design cognition, and empirical evidence regarding problem-solving and decision-making, spatial cognition and navigational cognition. The extended alphabet, what "most people don't know," turned out to include a minimal model of navigation as a cognitive task, a detailed decomposition of navigational design domains, a set of design principles and three actual designs. A user study provided evidence supporting the utility of one of the designs, demonstrating the potential benefits of the derived principles and of the overall approach to supporting design.

[lxiv] [239] Reprinted from *ON BEYOND ZEBRA!*, Dr. Seuss, p. 47, ©1955, with permission from Random House Publications.

The process of supporting design by developing an understanding of navigation as a problem in design began by seeking a useful understanding of “a problem in design,” in general, and “a problem in user interface design,” specifically. Studies of the design process identified four phases: problem analysis, design generation, design realization and design evaluation. Of these, supporting the first two offered the greatest opportunities for helping designers meet design goals more rapidly and more consistently. Studies of design cognition provided evidence that knowledge of invariant design constraints plays a key role in these phases and suggested that identifying and articulating specific design constraints might prove useful. A brief examination of the needs of user interface design exposed cognition as a critical source of constraints, and suggested that specific knowledge of how cognitive task performance is affected by manipulation of environmental features might help designers.

This led to the formulation of a process for deriving invariant constraints on navigational design from psychological knowledge, the design knowledge development process. This process comprises four steps: (1) developing an understanding of navigation as cognitive task, (2) detailing the relationships between this task and navigational design, (3) deriving implications for design of those relationships, and (4) understanding how to apply those implications during actual design. The knowledge needed in the first two steps, fortunately, appeared to be available in existing psychological knowledge. The method thus outlines a means of extracting design knowledge from psychological knowledge.

The first step of the process—developing an understanding of navigation as cognitive task—entailed analysis of an extensive and diffuse body of literature. This analysis revealed terminological conflicts, but, for the most part, conceptual agreement. Identifying areas of agreement (and imposing a consistent terminology) yielded a description of four subtasks of navigational cognition: information-gathering, spatial knowledge preservation, wayfinding and locomotion. Analysis of apparent disagreements revealed that the commonly assumed relationships among these subtasks are not reduced to those that are cognitively fundamental, but include relationships induced by physical environments. The resulting design-oriented model of navigation as a cognitive task consequently differs slightly from the psychology-oriented model that is commonly offered. These differences may reflect differences in focus between design and psychology—the former seeking to describe minimum necessary behavior, the latter to describe observed behavior. They may also reflect differences in environmental assumptions—most models of observed behavior seek to account for behaviors observed in the physical world, where the purpose of the present model is to account for behaviors in any environment.

The second step of the design knowledge development process—detailing the relationships between the cognitive task of navigation and navigational design—entailed developing a taxonomy of navigational design. This taxonomy decomposes navigational design along two dimensions: cognitive function of manipulation (locomotional, informational, steering) and design element manipulated (prosthetic, environmental). All six design subdomains potentially affect performance of any of the four navigational, so the problem of understanding navigation as a problem in design can be decomposed into 24 subproblems (Figure 3). As wayfinding was deemed the most fundamental of the cognitive tasks and environmental locomotional design at the core of wayfinding problems, further effort was restricted to understanding wayfinding as a problem in environmental locomotional design. Restricting the design knowledge development process to be applied to this subproblem (Figure 4) and the first two steps to be revisited with an eye to greater detail.

In revisiting the first step, no models of wayfinding as a cognitive task were found to be available. However, wayfinding is commonly considered to be, and was here defined as, a problem-solving and decision-making task, so three models of general problem-solving and decision-making were considered. Although these exhibited critical differences, they also showed extensive commonalities, including a common underlying process. This yielded a generalized model that could be combined with empirical evidence surrounding wayfinding cognition to form the design-oriented model of wayfinding as a cognitive task comprising four subtasks: path detection, route prediction, route selection and route following.

Revisiting the second step required continued analysis of the empirical evidence surrounding wayfinding cognition. This was guided by the design-oriented model of wayfinding developed in the first step and revealed that four factors determined, at least in part, by environmental locomotional design have been shown to affect wayfinding behavior and performance: the locomotional structure available to the wayfinder, the relationship between the locomotional structure and information access points, the relationship between movement and the locomotional structure, and the relationship between steering and the locomotional structure.

The third step of the design knowledge development process—deriving implications for environmental locomotional design from the relationships between wayfinding cognition and environmental locomotional design—focused on expressing the design constraints implied by the relationships between wayfinding behavior and performance and these four factors as design principles. This resulted in a set of twelve principles.

The fourth step of the design knowledge development process—understanding how to apply those implications during actual design—was begun simultaneously with the third. It resulted in the Repeat File Access design for everyday file system interaction in a desktop environment that was developed simultaneously with the twelve design principles. This design complements existing designs for file system interaction. It differs from existing designs by concentrating on the finding and searching subtasks of file system interaction. This results in a design that is focused on wayfinding. The conjectural task analysis upon which the design is based implies that the existing designs are more focused on the browsing subtask and may be more focused on spatial knowledge preservation. The implication is that the proposed design complements the existing designs rather than replacing them.

The initial exploration of the fourth step of the design knowledge development suggested that satisfaction of the design principles implies a certain design process. This process was outlined and its use illustrated in further exploration of the fourth step, which was aimed at developing general support for navigation in a spatial multiscale environment. Initial efforts focused on searching and finding as these subtasks underlie most interaction in spatial multiscale. Conjectural task analysis combined with some design intuition resulted in two separate designs, the Voronoi-based design and the cluster-based design. The cluster-based design is based on spatial cluster analysis and the design developed here assumes an algorithm that yields a hierarchical structure of nested object groupings. The resulting design, consequently, employs a hierarchical locomotional structure that may not be suitable for all tasks. This design conforms to all 12 design principles.

The Voronoi-based design is applicable to a greater range of tasks than the cluster-based design. It employs a locomotional structure that results from interaction between the object layout and the viewing window. Destination selection is based on the location of the mouse at any given time. This design appears to violate two of the 12 design principles, yet intuitions, borne out by empirical study, suggested that it was a viable design nonetheless. Three additional design principles were hypothesized describing properties of environmental locomotional design that may affect wayfinding behavior and performance, but which have not been explored in the psychological literature. These factors may compensate for the two principles that were violated and account for the success of the design.

The three designs developed appear widely different and support different tasks in widely different environments. Nonetheless, a generalized algorithm for supporting movement, Predictive Targeted Movement, was identified as underlying all of them. This algorithm resembles the cognitive wayfinding process, and allows the designer to specify specialized interaction for any of the four subtasks.

Finally, a user study comparing the Voronoi-based design to a conventional design for navigation in spatial multiscale was conducted. Results from this study showed that the Voronoi-based design increased task performance significantly and appeared to decrease both physical and cognitive overhead of wayfinding. Results from one experiment, the Desert Fog experiment, showed, conclusively, that modifying the environmental locomotional design can alter the wayfinding task fundamentally.

Future Work

And I saw that my troubles were not *at an end.*
Dr. Seuss, *I Had TROUBLE in Getting to SOLLA SOLLEW*[lxv]

The present work has expended considerable effort in defining the problem of understanding something as a problem in design, developing a process for extracting design knowledge from psychological knowledge, and applying that process to understanding wayfinding as a problem in environmental locomotional design. It has yielded a general model of navigation as a cognitive task, a taxonomy of navigational design, a model of wayfinding as a cognitive task, a set of fifteen design principles and demonstrated potential effects on wayfinding performance of manipulating environmental locomotional design. In spite of these results, the work has posed more questions and left more questions unanswered than it has answered. Future work is possible and planned at many levels and in many directions.

First, work is planned in pursuit of the goal of supporting design by making critical design knowledge explicit and available to designers. This work includes continuing to validate the utility of the principles developed thus far. This entails applying them to further design situations, particularly support for other tasks and other interaction environments. It also requires application of the principles by other designers and testing the resulting designs. While this appears to be a simple task, it is complicated by the difficulties of communicating complex information reliably and systematically.

Another planned approach to validating the utility of the principles is to use of the principles in analyzing existing designs. If the principles can be expected to prevent usability problems during design generation, they should also be able to identify problems during design evaluation. Ideally, such validation would use the principles to identify potential usability problems or improvements in designs that had been or could be subject to user testing, so that the analytical and empirical results could be compared. This use must, again, eventually be proven successful in the hands of others.

Work is also planned to continue to develop the overall approach of supporting design by making design knowledge explicit. This entails further applications of the proposed process for extracting design knowledge from psychological knowledge, including applying the process to other subproblems of understanding navigation as a problem in design, focusing first on environmental informational in support of wayfinding. The process and overall approach should also be explored in other psychological task domains. Work is planned to examine implications of the cognition of learning for design that facilitates incidental learning (learning that occurs as a side effect of tool use and task performance). Note that the present work has shown that existing psychological knowledge is likely to be insufficient for design purposes, so a key directive of this future work is to determine what additional types of knowledge are needed and how they may be obtained.

The second direction of future work is to continue the design efforts already begun. Work is planned to complete the implementation of the Voronoi-based navigation design, to include the features not implemented in the version used in the study (e.g., consideration of information access points and imposition of “speed bumps”), and to subject this implementation to further user studies. Given that subjects in the study were frustrated at not being able to get to information access points that were just outside the view, it is expected that these will increase performance and user satisfaction.

A related effort is to explore the possibilities of using Voronoi tessellation of space as a basis for interaction. As the Voronoi-based design demonstrated, this is potentially a powerful means of facilitating movement and object selection. It might be used, for instance, to aid target acquisition, e.g., selecting icons on the desktop.

Implementation and study of the cluster-based design and the file system interaction design are also planned. The former raises opportunities to incorporate metrics for spatial analysis that recognize more than simple spatial clustering, for instance, recognizing common layout patterns in specialized application domains such as

---

[lxv] [240] Reprinted from *I Had TROUBLE in Getting to SOLLA SOLLEW*, Dr. Seuss, p. 34, ©1965, with permission from Random House Publications.

chemistry or meteorology. It also offers the opportunity to contrast the cluster-based and Voronoi-based designs. The latter, as mentioned, poses a significant challenge in developing a mechanism to monitor file access and use (a classic challenge, for instance, is detecting whether an open file is actually in use or whether the user has gone to lunch). This is related to another significant challenge, that of devising an appropriate formula for use of this information, and, as with any adaptive design, ensuring that different user preferences and behaviors are accommodated.

The third direction of future work lies in experimenting with ways of incorporating the design knowledge developed into software engineering techniques and tools in order to facilitate both design and development of software applications. The initial effort is to incorporate the Predictive Targeted Movement algorithm and the high-level cognitive concepts and constraints it relies upon in application frameworks. A prototype of such application framework components was developed during the implementation of the Voronoi-based design and is available for public use [114]. However, the implementation needs to be generalized and deployed. Studies may then be conducted to examine whether and how the revised framework affects both the development process and its resulting products.

Finally, the present work offers opportunities for future work of a psychological nature. This includes further analysis of the experimental data, e.g., to examine whether and how much influence factors such as spatial ability or age have on performance, and to understand how the differing locomotional structures affect wayfinding behaviors and strategies.

Open Questions

In addition to the opportunities presented for future work, the present efforts leave several open questions. These questions also offer opportunities for future work, but lead deeply into fields other than design so expiring them is not planned, at this time.

First, several unanswered psychological questions were identified in the course of analyzing the literature and synthesizing design constraints. These are summarized in *APPENDIX D Open Psychological Questions*, p. 301. They include the three hypothesized design principles, which directly represent untested but testable psychological hypotheses.

Second, the work has timidly, and barely, touched on understanding the mathematical implications and underpinnings of interaction based on Voronoi tessellations of space. Analysis of the Voronoi-based design relied primarily on proof by example. Formal proofs might yield both deeper understanding of why the designs achieve (or fail to achieve) certain effects as well as suggesting ways in which they can be improved or new aspects to explore. For instance, determining a means of enumerating branch regions in the Voronoi-based locomotional structure (see *APPENDIX E Voronoi Problem Statement*, p. 303, for a specification of the underlying mathematical question) might reveal a strategy for reducing their number or limiting damaging effects from a high number. Although such questions are fundamentally mathematical, this area of effort complements the design exploration of interaction using Voronoi tessellations described above (*Future Work*, p. 272).

Third, a large body of literature exists that examines the nature of spatial language. This literature was not brought to bear on the present efforts, first, because of the complexity of the questions it raises and the answers it proposes, and, second, because of the difficulty of determining the relationship between these answers and design. The most fundamental questions that must be understood for this literature to be brought bear on understanding design is, of course, the relationship between language and cognition. Presumably, language reflects cognition in some way (must, indeed, do so or it could not serve as a useful medium for thought or communication). The exact nature of this relationship has been examined extensively by psycho-linguists and has resulted in a large body of literature [27, 162, 165].

The second question that must be answered is that of the relationship between language and the external world. Spatial language must reflect the external world in some way, and semantic theories have been developed to explain this relationship [130]. In order to apply such theory to understanding design, the relationship between language and perception [185] must also be examined, since perception clearly must play a mediating role between language about the external world and the external world.

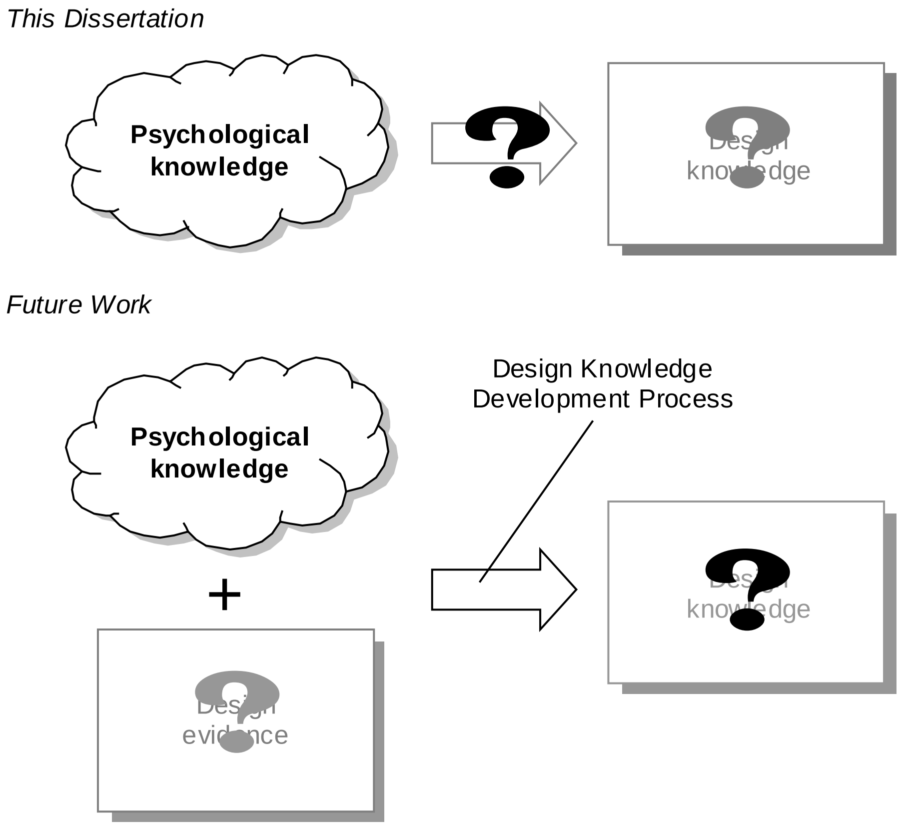
As an example of the difficulties posed by these questions, consider the common observation that the same language is frequently used to describe both spatial and temporal concepts [108]. This may reflect the space-time duality studied by physicists (known as the "space-time continuum" to science fiction fans), i.e., indicate an external reality. It may reflect the use of analogous reasoning, i.e., indicate a cognitive connection between the two. It may reflect evolutionary parsimony, i.e., indicate neither an external reality or a cognitive connection, but merely a mechanism of convenience. Or, as is most likely, it may reflect some combination of all three.

Regardless of the answers to these questions, it is clear that examination of the literature on spatial language, potentially offers deep insights into design to support spatial and navigational cognition. However, it also clear that such examination is, in itself, a major undertaking. Note that an in-depth examination of this literature is only necessary if it is to be used to understand the implications of the underlying cognition for design; if the aim is to inspire design, i.e., make use of one or more of the implications without necessarily understanding it, brief forays into the literature are likely to be sufficient.

Conclusions

Only three definitive conclusions can be drawn from the present work. First, the Desert Fog experiment showed that the locomotional design can alter the complexity of the wayfinding to the extent of making the impossible possible. Second, the Grid Markers experiment showed that judiciously constrained movement can increase wayfinding performance and decrease the physical and, possibly, the cognitive overhead of navigation. Third, the identification of the PTM algorithm demonstrates that high-level cognitive tasks, such as wayfinding, can be considered during low-level interaction design, such as developing support for movement. However, the work offers evidence in support of several provisional conclusions.

First, the differences between the commonly offered psychological model of navigation and the design-oriented model developed here support the supposition that design knowledge and psychological knowledge differ—at least in the context of user



This dissertation has proposed and tested a process for developing design knowledge from psychological knowledge in a somewhat "transparent" domain, i.e., a domain in which the outcome was not entirely unanticipated. The design knowledge development process is now sufficiently understood that it may now be applied in domains where the outcome is unknown. Note that the present work has shown that existing psychological knowledge is insufficient and must be augmented with evidence from other sources—perhaps from experience with prototypical designs—to produce complete design knowledge.

Figure 84 Developing a process for extracting design knowledge in a "known" domain before applying it in an "unknown" domain.

interface design, and offers a detailed example of some of the differences. The differences are made even more apparent by the descriptive nature of the psychological knowledge offered in Chapter 3 and the prescriptive design knowledge offered in Chapter 4.

Second, the initial set of twelve design principles supports the supposition that user interface design knowledge can be extracted from existing psychological knowledge and offers a case study of doing so. This study suggests that such derivation may not be a simple or straightforward task. For example, Lynch's work is highly significant to understanding spatial cognition, resulting in an extensive discussion here (cf. Chapter 2 *Lynch: Elements of Cognitive Maps,* p. 82, and Chapter 3 *Environmental Elements in Mental Representations*, p. 121) and multiple prior efforts to apply his results directly to design (cf. Chapter 2 *Design Principles and Guidelines,* p. 82). Despite this prominence in psychology, Lynch's work plays a small, albeit important, role in the design knowledge developed here.

Finally, the need to hypothesize additional principles to account for apparent contradictions between psychological knowledge and evidence from design supports the tentative conclusion that existing psychology is not sufficient to meet the needs of design. This is contrary to the original expectations of the dissertation. While the dissertation has identified specific areas in which further psychological evidence is needed, it has also suggested that additional types of psychological evidence are needed. Specifically, design requires more detailed information about the effects of systematic environmental manipulations on cognitive behavior and performance than psychology is wont to provide. It also requires detailed evidence for potential interactions between different environmental manipulations, e.g., the hypothesized effect of alternative routes as compensating for increased plan complexity (Chapter 4, *Principle 14 Alternative Routes*, p. 224). Finally, it may require different understandings of environmental elements, e.g., the need to elaborate the psychological concept "branch point" into the design concepts of "branch region," "branch region boundary," "branch region entry port," and "branch region exit port."

The most immediate contributions of the work are, of course, the set of design principles, the empirical evidence provided by the user study, the application framework components developed for the study, the PTM algorithm and the three designs themselves. The design-oriented model of navigation, the taxonomy of navigational design, the design-oriented model of wayfinding and the vocabulary introduced are less tangible, but no less important, contributions. They unify and make sense of an extensive and, hitherto, diffuse and rather confusing literature. Even less tangibly, but perhaps more importantly, the work provides detailed specific examples of differing requirements of design and psychology, as well as detailed specific examples of the limitations of the use of existing psychological knowledge for design.

Finally, and perhaps most importantly, the work offers a specific process for making key design knowledge explicit, the design knowledge development process. Although this process is heuristic, it provides a guideline for identifying key design elements and constraints upon them. The process was developed and applied in the relatively simple and cognitively well-understood domain of navigation. The results of its application, consequently, were not entirely unexpected.

For example, many of the derived principles may seem self-evident, that is, they could have been derived from intuition and general principles of user interface design. The designs resulting from their application, similarly, while offering novel aspects, could probably have been developed without aid of the principles. Nonetheless, it is unlikely that all the principles would be derived, collectively, from intuition, and it is likely that developing the designs without the principles would require multiple iterations of the design cycle. (In fact, some of the "obvious" elements immediately suggested by application of the principles, e.g., the direct links to particular files in the file system design, known as "short-cuts" or "aliases," were only added to the Macintosh desktop environment after six years of evolutionary design iterations.)

This transparency of the navigational domain aided in the development of the process, precisely because the key design elements and possible design constraints were somewhat imaginable. The need for a systematic process, however, becomes clear in a domain where key design elements and constraints are not as readily discernible (Figure 84), for example, in a cognitively more complex domain such as learning. The immediate value of the process is to provide designers with explicit design knowledge. The long-term value is to reduce the need for designers or developers to acquire and apply the knowledge explicitly by embedding the knowledge in software design and development tools and techniques. Thus, while the present work may only offer few definitive conclusions, it lays the groundwork for a plethora of future conclusions, shows how to get from "brains" to "branch points" and beyond, and provides some indication of what to do when you get there.

APPENDICES

APPENDIX A

Document Map

APPENDIX B
Glossary

behavior, cognitive: a pattern of mental actions that changes mental state or initiates physical action

branch point: psychological term for a location where the available locomotional options change and a decision is executed; cf. *branch region*

branch region, automated: a branch region at which no action is necessary to select the *default* option; cf. *manual branch region*

branch region, exposed: a branch region about which information is available at a preceding or coinciding *information access region*

branch region, hidden: a branch region about which no information is available at preceding or coinciding *information access regions*

branch region, manual: a branch region at which action must be taken to select an option; cf. *automated branch region*

branch region, phantom: non-existent branch region; cf. *false information access region*

branch region, poorly-automated: automated branch region in which the default option is incorrect or unexpected

branch region, well-automated: automated branch region in which the default option is a correct option

branch region complexity: in the context of locomotional design, the number of options offered by a branch region

branch region option: a locomotional option offered by a branch region

branch region option, default: the option selected automatically if no action is taken at an *automated branch region*

branch region option, exposed: a branch region option about which information is available at a preceding or coinciding *information access region*

branch region option, hidden: a branch region option about which no information is available at preceding or coinciding *information access regions*

branch region option, viable: a branch region option that will allow the wayfinder to reach the desired destination

branch region: design term for a set of contiguous locations within which the same locomotional options are available and a decision can be executed; cf. *branch point*

branch region entry pass: a *branch region pass* where all locomotional options offered by the region become available; cf. *branch region exit pass*

branch region exit pass: a *branch region pass* where one or more of the locomotional options offered by the region become unavailable; cf. *branch region entry pass*

branch region pass: a set of contiguous locations on the boundary of a branch region where the locomotional options change

browsing: the task of understanding or gaining knowledge of the contents or structure of an environment

cognitive function: the role a design or design element plays in the performance of a cognitive task

cognitive map: a mental representation of spatial information that includes viewpoint-independent knowledge of spatial relationships among environmental features

cognitive mapping: the process of developing a *cognitive map*

constraint, design: a limitation defining what constitutes an acceptable solution to a design problem

decision point: a location at which a wayfinding decision can or must be made; cf. *branch point, information access point*

design evaluation: design phase aimed testing whether a proposed solution addresses or can be expected to address the design problem satisfactorily

design generation: design phase aimed at producing ideas, at varying levels of detail, of how design problems might be addressed

design realization: design phase aimed at producing a tangible representation of a design solution

destination: a location that must be reached in order to accomplish the task in whose service navigation is undertaken; cf. *target location*

environmental design: design of properties of the environment itself; cf. *prosthetic design*

environmental locomotional design: subdomain of navigational design; the design of what movement is made possible by an environment, including where it is possible to go and how it is possible to get there

finding: the external task of going to a location or object in the environment with confidence in the knowledge of where it is or how to get to it

generality: a dimension of constraint characterization that describes the degree to which a constraint applies to a particular class of problems or type of design situation; augments the dimensions defined by Lawson

inappropriate constraint: design constraint that applies to no problems of a particular type

information-gathering: a subtask of navigation; the process of collecting information about the environment, such as where places and things are and how they are related spatially

information, natural: information made available through *perceptual design* and characteristics of objects in the environment alone; e.g., a unique-looking rock

information, synthetic: descriptive information deliberately added to the environment, e.g., signage

information access point: psychological term for a location at or from which information may be perceived; cf. *information access region*

information access region, false: information access region that provides information about a *phantom* branch region

information access region, natural: location at or from which natural information may be perceived

information access region, synthetic: location at or from which synthetic information may be perceived

information access region: design term for a set of contiguous locations at or from which particular information may be perceived; cf. *information access point*

information access region pass: a set of locations on the boundary of an *information access region* at which the information offered by the region becomes or ceases to be available

information access region entry pass: an *information access region pass* at which at which the information offered by the region becomes available; cf. *information access region exit pass*

information access region entry pass: an *information access region pass* at which at which some or all of the information offered by the region ceases to be available; cf. *information access region entry pass*

information point: location at which information is present

information point, natural: location at which natural information is present

information point, synthetic: location at which synthetic information is present

informational design: design of what information is available to the navigator perceptually

invariant design constraint: a design constraint that applies across all designs of a particular type

layout: the logical and spatial relationships among environmental elements, specifically locations and paths when used in the context of locomotional structure; also called *plan*

locomotion: a subtask of navigation; the task of directing and controlling movement for the purpose of moving between distinct locations

locomotional design: design of what movement is possible, including locations, paths, movement and relationships among them, as well as means of effecting movement

locomotional structure: a set of interconnected locations and paths

locomotional structure, actual: a locomotional structure that is actually available to the wayfinder

locomotional structure, perceived: a locomotional structure the wayfinder believes to be available

mechanism, cognitive: the mental and physiological structures and processes by which *cognitive behaviors* are effected

navigation: a complex of cognitive activities associated with the task of determining where places and things are, how to get to them and actually getting there. It entails determining what movement is necessary, controlling movement and actually moving.

navigational design: design that affects navigation, including design of an environment, augmentation of an environment, and design of specialized aids

path: a connection that allows locomotion between two locations

path-identification: a subtask of wayfinding; the task of understanding the status, attributes, and dynamics of locations and paths in the environment.

perceptual design: the design of sensory stimuli and their behavior

perceptual structure: the aspect of *perceptual design* that determines where in the environment sensory stimuli may be perceived

plan: the logical and spatial relationships among environmental elements; in the context of locomotional structure, relationships among locations and paths; also called *layout*

plan complexity: quantifiable attributes of plan relationships; in the context of locomotional design operationalized as number of destinations, routes and branch points, etc. in a locomotional structure

plan organization: logical attributes of plan relationships, e.g., dictating what routes are available in a locomotional structure

Predictive Targeted Movement (PTM): generalized algorithm for designing and supporting movement

problem analysis: design phase aimed at understanding the problems a design should or is failing to address

prosthetic design: design of aids that allow the navigator to detect or make use of environmental properties; cf. *environmental design*

route: a *path* that leads to a *destination* or that must be followed in order to accomplish the goals of the task in service of which navigation is undertaken; cf. *target path*

route complexity: in the context of locomotional design, the number of branch points along a given route

route-prediction: a subtask of wayfinding; the task of predicting which locations might be destinations, and which paths might represent routes to the desired destination

route-selection: a subtask of wayfinding; the task of selecting which of a set of possible paths to take

route-following: a subtask of wayfinding; the task of matching environmental and conceptual features to ensure that movement follows the selected path and route

searching: the external task of seeking a location or object within the environment that meets certain criteria without certitude in prior knowledge of where it is or how to get to it

spatial knowledge preservation: a subtask of navigation; the task of encoding and storing spatial knowledge for future need, as well as recalling and decoding such preserved knowledge

steering design: design of the relationship between human action and movement within the environment, and of tools to control movement

target acquisition: the external task of guiding oneself or some other object to a location or object that is in the current view (i.e., perceptually available)

target destination: a *destination* that is a goal of a given wayfinding task; also called *target location*

target location: a *destination* that is a goal of a given wayfinding task; also called *target destination*

target path: a *path* that meets the needs of a given wayfinding task

task, cognitive: a set of mental functions to be performed, described in terms of the goals to be achieved by performing those functions

task, external: a task whose goals include effecting change outside the mind, including, potentially, changes in the minds of others

task-defined structure: the locomotional structure that is inherently necessary to task completion

task logic: in the context of locomotional design, the logic underlying the organization of the *task-defined structure*, and, if applicable, determining the order in which destinations and routes are needed

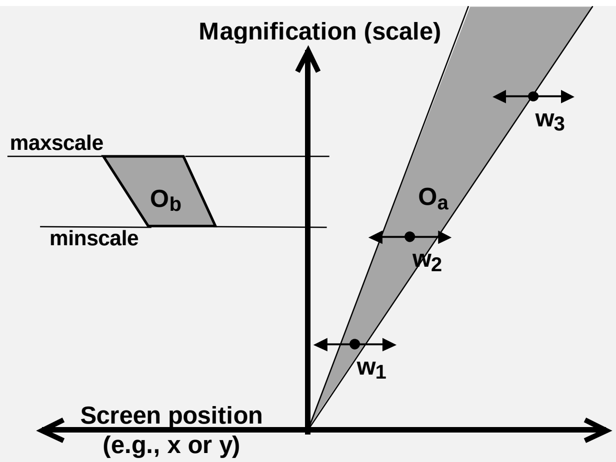
usability: the quality of how well a tool meets the needs of its user

user interface, electronic: tool that allows people to direct the activities of a computational device or an electronic tool that allows people to perceive and manipulate properties of a physical device

variant design constraint: a design constraint that applies to some but not all designs of a particular type

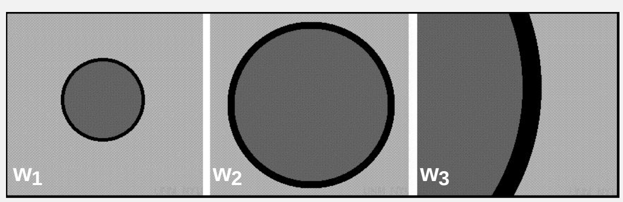
wayfinding: a subtask of navigation; the spatial problem-solving and decision-making entailed in determining what movement is necessary or desirable in order to accomplish a task

APPENDIX C
Understanding Space-Scale Diagrams*



Space-scale diagrams were developed as a tool for understanding multiscale spaces [**82**]. They show the apparent change in size and position of an object relative to the magnification of the view. In the sample diagram above, the horizontal axis indicates location in screen-space (e.g., x-coordinate) and the vertical axis indicates degree of magnification (the scale-coordinate). Note that zooming "in" and "out" correspond to moving "up" and "down," respectively, in the diagram.

In the simple case, an object only grows in size as it is magnified. Such geometrically-scaling objects, like $\mathbf{O_a}$ in the sample diagram, have a V shape in a space-scale diagram, indicating that the object appears to be infinitely small at infinitely small scales, and grows larger as the view is magnified. In practice, an object typically has a minimum magnification at which it is rendered, its *minscale*, or automatically disappears when it is smaller than one pixel. Objects also have a maximum effective magnification, the *maxscale;* e.g., when they fill the view uniformly they are often culled by the rendering system. These limits are shown schematically for object $\mathbf{O_b}$ in the sample diagram.



A particular view of the world is defined by the position in space and scale of a window with a given width. This is represented in a space-scale diagram by a horizontal line whose midpoint represents of the center of the window. (Note that we assume uniform magnification across any particular view.) Since the width of the window is unaffected by the magnification of the view, a line representing a particular window will have the same width throughout the diagram. In the sample diagram, $\mathbf{w_1}$ is a view in which $\mathbf{O_a}$ fills the middle third of the window, as shown in the first of the screen-shots above. $\mathbf{w_2}$ has zoomed in on (the now magnified) $\mathbf{O_a}$, as shown in the second screen-shot. $\mathbf{w_3}$ has zoomed in further and panned right almost half a window width, as shown in the third screen-shot.

* Reprinted with permission from Jul, S., Furnas, G. W. (1998). Critical Zones in Desert Fog: Aids to Multiscale Navigation. *ACM Symposium on User Interface Software and Technology, UIST 98,* 97-107.

APPENDIX D
Open Psychological Questions

- What is the role of constraints in design problem *solving*? (Cf. Lawson [161].)
- What is the relationship between navigation in the physical world and in electronic environments?
- Is the postulated design-oriented model of navigation, in particular, the lack of the need for preserved knowledge in wayfinding, psychologically valid?
- What is the role of edges in spatial knowledge and wayfinding? (Cf. Lynch [172].)
- What exactly distinguishes functional levels of spatial knowledge from spatial levels of spatial knowledge and what are the implications these distinctions? (Cf. Teske and Balser [265].)
- What are the consequences of changing locomotional structure dynamically, e.g., for games or learning purposes, and what properties can be manipulated?
- What is thee effect of discontinuities in plan organization on spatial knowledge preservation, wayfinding behavior and performance? (Cf. Dada and Wirasinghe [57].)
- How does the relationship between task logic and organizing principle of a locomotional structure affect wayfinding and spatial knowledge preservation?
- What are the factors that affect the trade-off between the number of branch regions and the number of branch region options?
- How does branch region automation affect wayfinding and spatial knowledge preservation?
- How do alternative routes affect wayfinding performance and success?
- How do hidden branch regions and hidden branch region options affect wayfinding and spatial knowledge preservation?
- How does speed of movement affect sense of spatial distance (e.g., constant speed vs. slow-in-slow-out)?

APPENDIX E
Voronoi Problem Statement

This is a description and motivation of the mathematical problem underlying the calculation of the number of branch points (and branch point options) in the Voronoi-based design offered for inter-object navigation in a multiscale environment.

CONTEXT

I am working on an user interface that uses mouse proximity to control viewpoint movement in a 2D zooming space. In effect, there are n objects laid out on an infinite 2D surface. The user can look at them with a magnifying window so the view can contain a rectangular region of any size. (See http://www.cs.umd.edu/hcil/jazz/play/hinote-0.5/jazz-mid-talk.htm for an interactive demo of such an environment.) When the user clicks to zoom in, the system selects the object that is closest to the mouse location and moves the viewpoint to be centered on that object, at a magnification that is reasonable for that object.

Clearly, selecting the object that is closest to the mouse divides the surface into regions within which all points are closer to one object than to any others. The boundaries between these regions are points that are equidistant between two objecs. This tessellation is known as a "Voronoi diagram" and the regions are known as "cells."

Since the user can only click on a cell that is contained in the viewing window, the set of cells that intersects a particular viewing window determines which objects can be reached from that view.

From a psychological perspective, changing the set of objects that can be reached represents a situation where the user must make a decision (i.e., whether to take the "about to be lost" option or to let it pass). Thus, the number of sets of cells that can be viewed uniquely represents the total number of distinct decisions that can be made during movement, and the total number of cells viewed in those sets represents the total number of options that can be considered. (These metrics, of course, represent the decisions made during a complete tour, not on any one individual trip.)

(Yes, there are details about decisions and options for moving the view out -- decreasing the magnification -- that can't be handled in this manner. They are handled separately so don't worry about them.)

So, I'm looking for an upper bound on the number of possible decisions and the number of possible options, or, more formally restated (I am not a mathematician, so forgive and correct any awkward phrasings):

PART 1

How many unique sets of Voronoi cells can be intersected by a rectangle of arbitrary size, given an arbitrary 2D Voronoi diagram?

* The rectangle may be subject to non-uniform scaling, but not rotation. However, if allowing rotation simplifies the problem, that number will do.

* "Intersect" is to be interpreted as "any portion of the cell contained in the rectangle."

* Note that the area of the cell contained in the rectangle and the positioning of the cell with respect to the rectangle are not significant. For example, all rectangles that intersect only cells A and B are considered isomorphic and are counted once as the set { A, B }.

* An upper bound is sufficient (although I'd like it to be reasonably tight).

For example, in a 1D (a linear world), the problem is simple:

```
Given n elements, there are
      1 set that intersects         n     cells
      2 sets that intersect         n-1   cells
      3 sets that intersect         n-2   cells
      ...
      n sets that intersect         1     cell
```

```
So, the number of unique sets is
      sum( i = 1, i <= n, i )
    = ( n^2 + n ) / 2               O( n^2 )
```

Interestingly, the "easy" diagrams in 2D (low n and regular layouts) also yield O(n^2). However, I don't know whether this is because these are best cases or because this is, in fact, an upper bound.

PART 2

What is the total number of cells intersected, counting a cell each time it appears? I.e., what is the sum of the cardinalities of the resulting sets?

* Again, an upper bound is sufficient.

In the 1D example, the answer is obvious from the above:

```
Total cell intersections is
        1 *   n
      + 2 * ( n - 1 )
      + 3 * ( n - 2 )
      + ...
      + n * 1
      = sum( i = 0, i <= n - 1, i * ( n – i + 1 ) )
      =   ( n + 1 ) * sum( i = 0, i <= n - 1, i )
        - sum( i = 0, i <= n - 1, i^2 )
      = ( n^3 + 3n^2 - 4n ) / 6           O( n^3 )
```

MOTIVATION FOR “COUNTING” THE TOTAL NUMBER OF POSSIBLE DECISIONS

Say you are on a committee overseeing the design of a museum. The floorplan is obviously constrained by a number of factors, such as traffic flow, size of objects in the collection, need for environmental control (e.g., dust, humidity, light), etc. The architect comes up with two floorplans that are quite different, but both meet all the committee's criteria. You, being the foresighted person you are, ask, "yes, but what about emergency evacuation? Is there a way to predict whether one of these designs would increase the chances of more people getting out faster?"

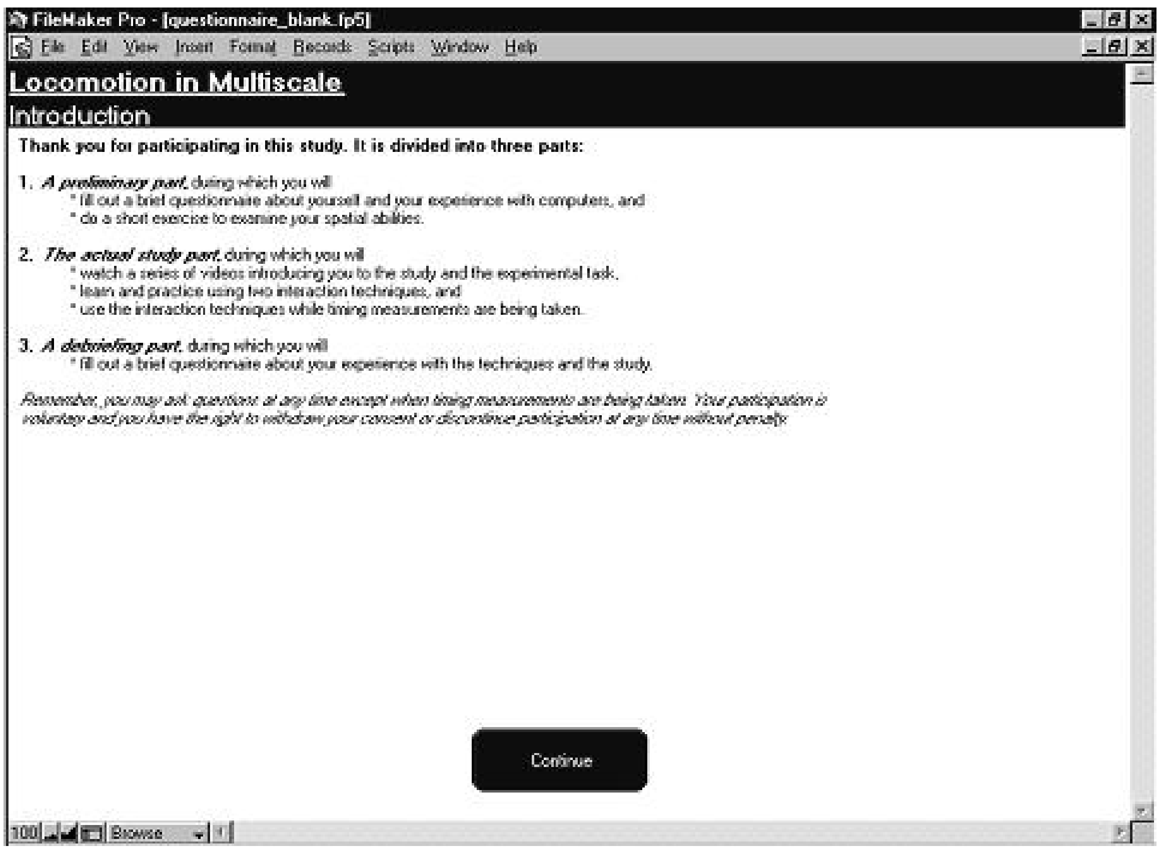
As it turns out, there is. Psychological studies show that there is a statistically significant correlation between the number of locations in a layout that require a decision (and the number of options at those locations), and the speed and accuracy with which people are likely to reach any given destination. Broadly said, the fewer chances you have for making a mistake, the less likely you are to make one (of course, whether you actually make one depends on a bunch of factors).

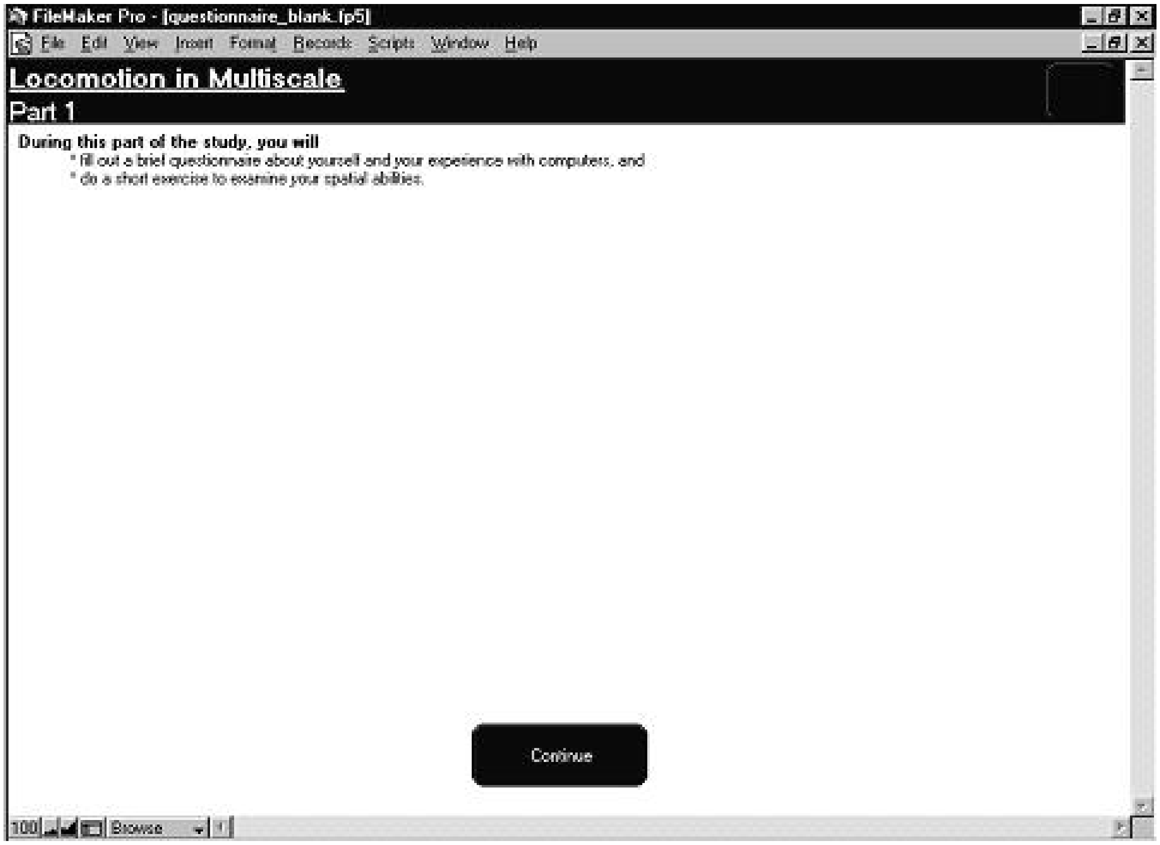
In many cases, interaction in an electronic environment is like an emergency evacuation -- you just want to get to your file, and don't care what you see along the way. So, how can I design an interaction mechanism that lets you go where you want to go as quickly as possible? Well, one strategy is to reduce the number of locations that require a decision.

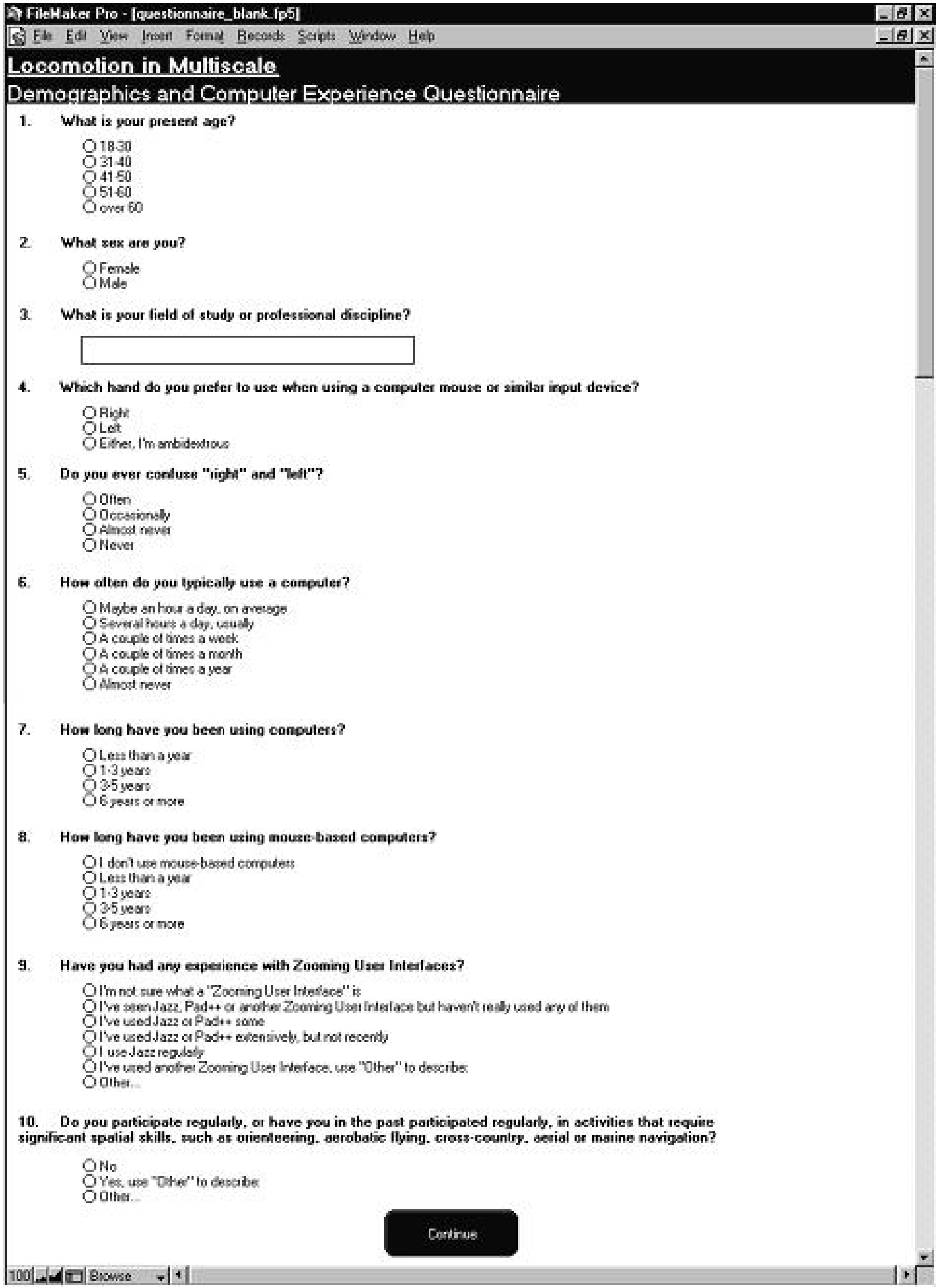
Now, in the design of electronic environments, I have an interesting opportunity. I may not be able to change the way things are laid out (you'd probably hate me if I started rearranging all your files, for example, organizing documents by authors' income (if people make more money, what they write should be more important, n'est pas?)), but I *can* change the connections that allow movement between them and how you control that movement. (In fact, I can even do it dynamically, to meet your immediate needs.) So I don't change where things are, but I change what you need to do to get to them. This may change the characterization of "locations that require a decision." In the present case, for instance, they turn out to be a places where the set of Voronoi regions that intersect the viewing rectangle changes. But, in order to determine whether I've reduced the number of such locations, I now have to have a means of counting them, or, since we're talking projected performance, at least place some bounds around how many there might be. In the case at hand, that means counting the number of unique ways in which the viewing rectangle can intersect Voronoi regions.

APPENDIX F
Experimental Questionnaire and Instructions

This appendix shows the sequence of screens subjects saw during the experimental evaluation. This was the means of obtaining demographic and other information from subjects and giving them an introduction to and instructions during the study. The screens are shown in the order in which they were presented to subjects, that is, the following screen is what subjects see when they press the “Continue” button.




FileMaker Pro - [questionnaire_blank.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Part 1
During this part of the study, you will
* fill out a brief questionnaire about yourself and your experience with computers, and
* do a short exercise to examine your spatial abilities.
Continue
100
Browse



FileMaker Pro - [questionnaire_blank.fp5]

File Edit View Insert Format Records Scripts Window Help

Locomotion in Multiscale

Demographics and Computer Experience Questionnaire

1. **What is your present age?**
   - ○ 18-30
   - ○ 31-40
   - ○ 41-50
   - ○ 51-60
   - ○ over 60

2. **What sex are you?**
   - ○ Female
   - ○ Male

3. **What is your field of study or professional discipline?**

4. **Which hand do you prefer to use when using a computer mouse or similar input device?**
   - ○ Right
   - ○ Left
   - ○ Either, I'm ambidextrous

5. **Do you ever confuse "right" and "left"?**
   - ○ Often
   - ○ Occasionally
   - ○ Almost never
   - ○ Never

6. **How often do you typically use a computer?**
   - ○ Maybe an hour a day, on average
   - ○ Several hours a day, usually
   - ○ A couple of times a week
   - ○ A couple of times a month
   - ○ A couple of times a year
   - ○ Almost never

7. **How long have you been using computers?**
   - ○ Less than a year
   - ○ 1-3 years
   - ○ 3-5 years
   - ○ 6 years or more

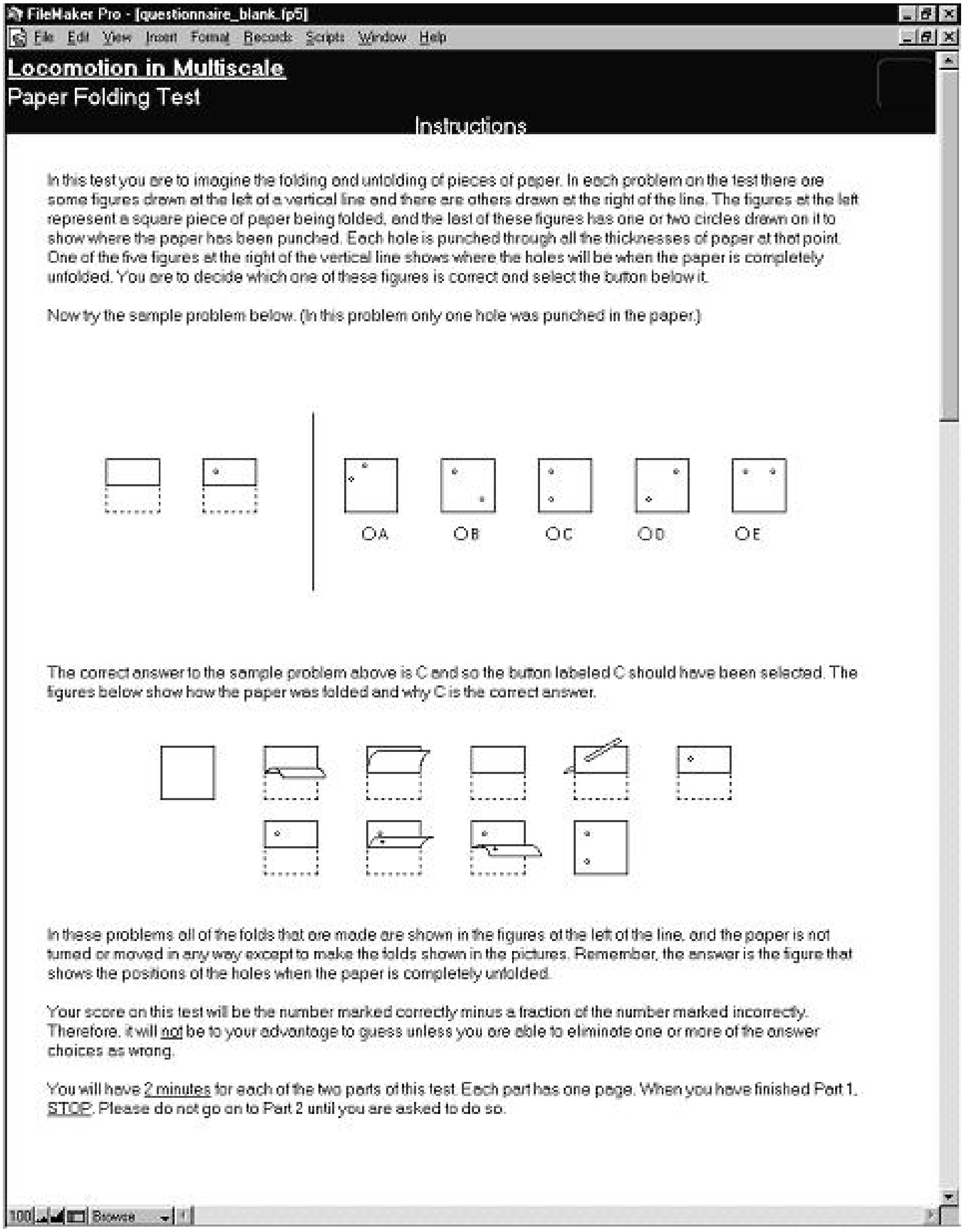
8. **How long have you been using mouse-based computers?**
   - ○ I don't use mouse-based computers
   - ○ Less than a year
   - ○ 1-3 years
   - ○ 3-5 years
   - ○ 6 years or more

9. **Have you had any experience with Zooming User Interfaces?**
   - ○ I'm not sure what a "Zooming User Interface" is
   - ○ I've seen Jazz, Pad++ or another Zooming User Interface but haven't really used any of them
   - ○ I've used Jazz or Pad++ some
   - ○ I've used Jazz or Pad++ extensively, but not recently
   - ○ I use Jazz regularly
   - ○ I've used another Zooming User Interface, use "Other" to describe
   - ○ Other...

10. **Do you participate regularly, or have you in the past participated regularly, in activities that require significant spatial skills, such as orienteering, aerobatic flying, cross-country, aerial or marine navigation?**
    - ○ No
    - ○ Yes, use "Other" to describe
    - ○ Other...

Continue

100 Browse



FileMaker Pro - [questionnaire_blank.fp5]

File Edit View Insert Format Records Scripts Window Help

Locomotion in Multiscale

Paper Folding Test

Instructions

In this test you are to imagine the folding and unfolding of pieces of paper. In each problem on the test there are some figures drawn at the left of a vertical line and there are others drawn at the right of the line. The figures at the left represent a square piece of paper being folded, and the last of these figures has one or two circles drawn on it to show where the paper has been punched. Each hole is punched through all the thicknesses of paper at that point. One of the five figures at the right of the vertical line shows where the holes will be when the paper is completely unfolded. You are to decide which one of these figures is correct and select the button below it.

Now try the sample problem below. (In this problem only one hole was punched in the paper.)

○A ○B ○C ○D ○E

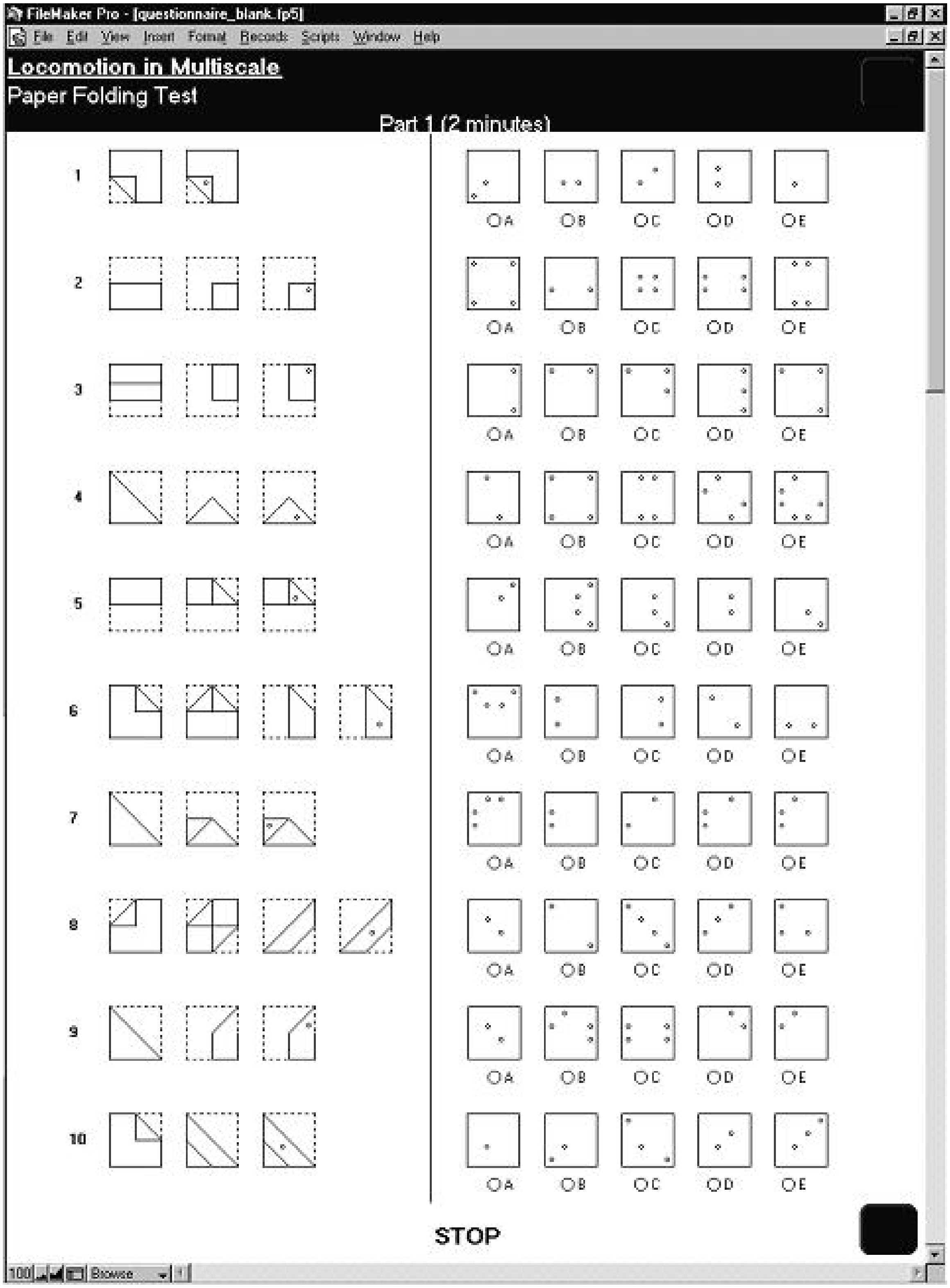
The correct answer to the sample problem above is C and so the button labeled C should have been selected. The figures below show how the paper was folded and why C is the correct answer.

In these problems all of the folds that are made are shown in the figures at the left of the line, and the paper is not turned or moved in any way except to make the folds shown in the pictures. Remember, the answer is the figure that shows the positions of the holes when the paper is completely unfolded.

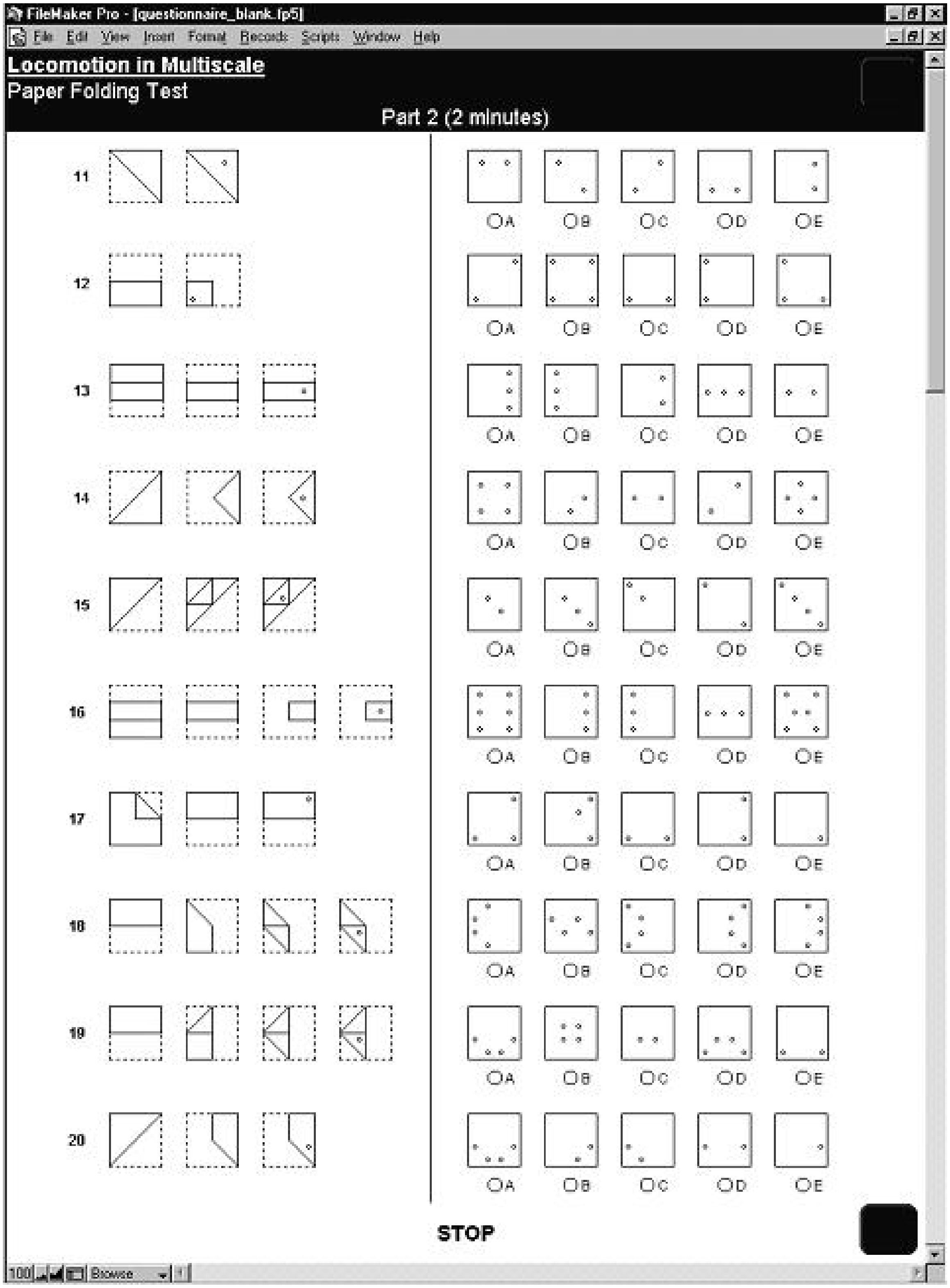
Your score on this test will be the number marked correctly minus a fraction of the number marked incorrectly. Therefore, it will not be to your advantage to guess unless you are able to eliminate one or more of the answer choices as wrong.

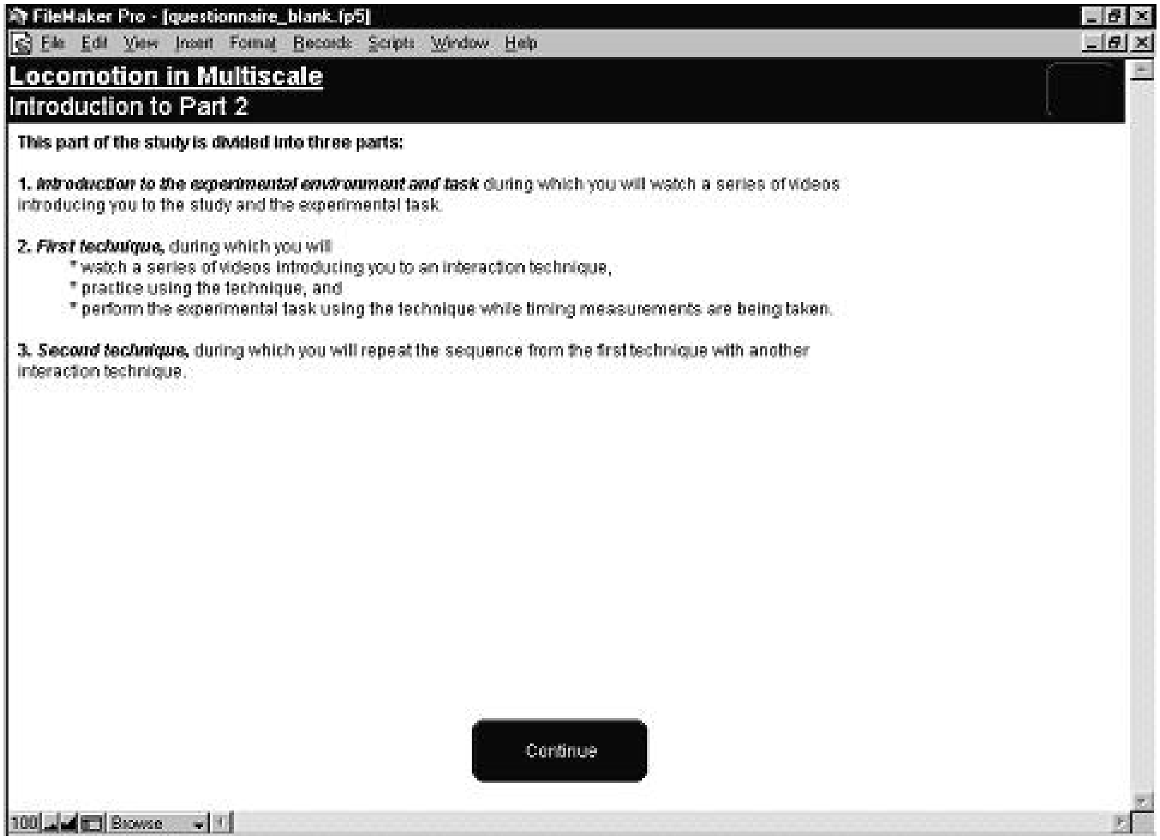
You will have 2 minutes for each of the two parts of this test. Each part has one page. When you have finished Part 1, STOP. Please do not go on to Part 2 until you are asked to do so.

100 Browse



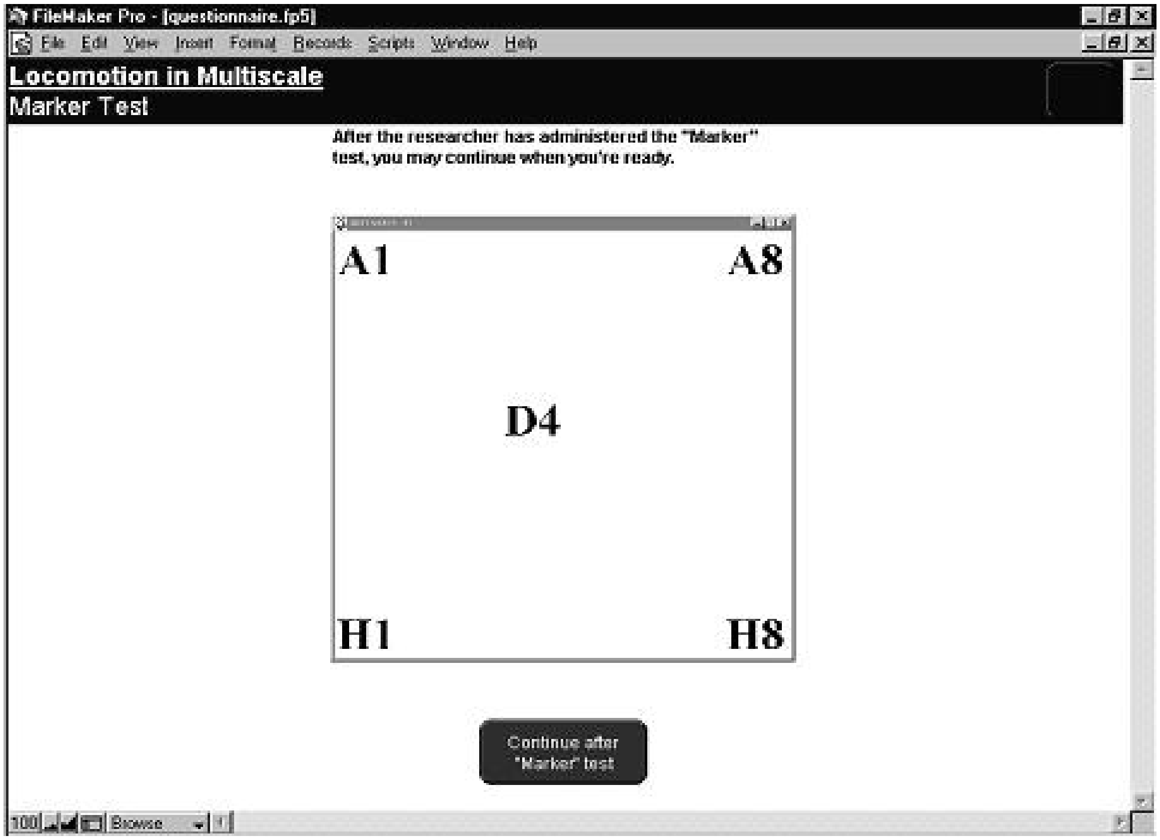
The two parts of the paper folding test were timed manually by the researcher.


FileMaker Pro - [questionnaire_blank.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Paper Folding Test
Part 2 (2 minutes)
11
A B C D E
12
A B C D E
13
A B C D E
14
A B C D E
15
A B C D E
16
A B C D E
17
A B C D E
18
A B C D E
19
A B C D E
20
A B C D E
STOP
100
Browse

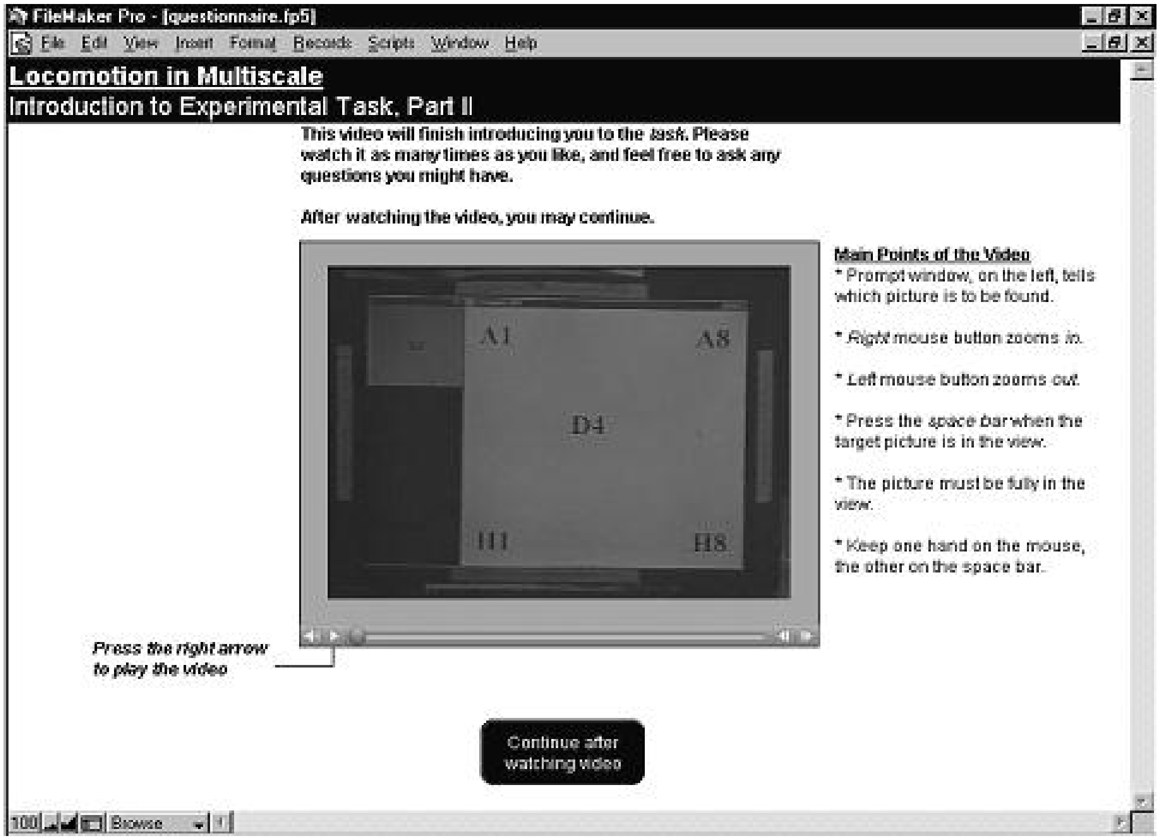

FileMaker Pro - [questionnaire_blank.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Introduction to Part 2
This part of the study is divided into three parts:
1. Introduction to the experimental environment and task during which you will watch a series of videos introducing you to the study and the experimental task.
2. First technique, during which you will
* watch a series of videos introducing you to an interaction technique,
* practice using the technique, and
* perform the experimental task using the technique while timing measurements are being taken.
3. Second technique, during which you will repeat the sequence from the first technique with another interaction technique.
Continue
100
Browse

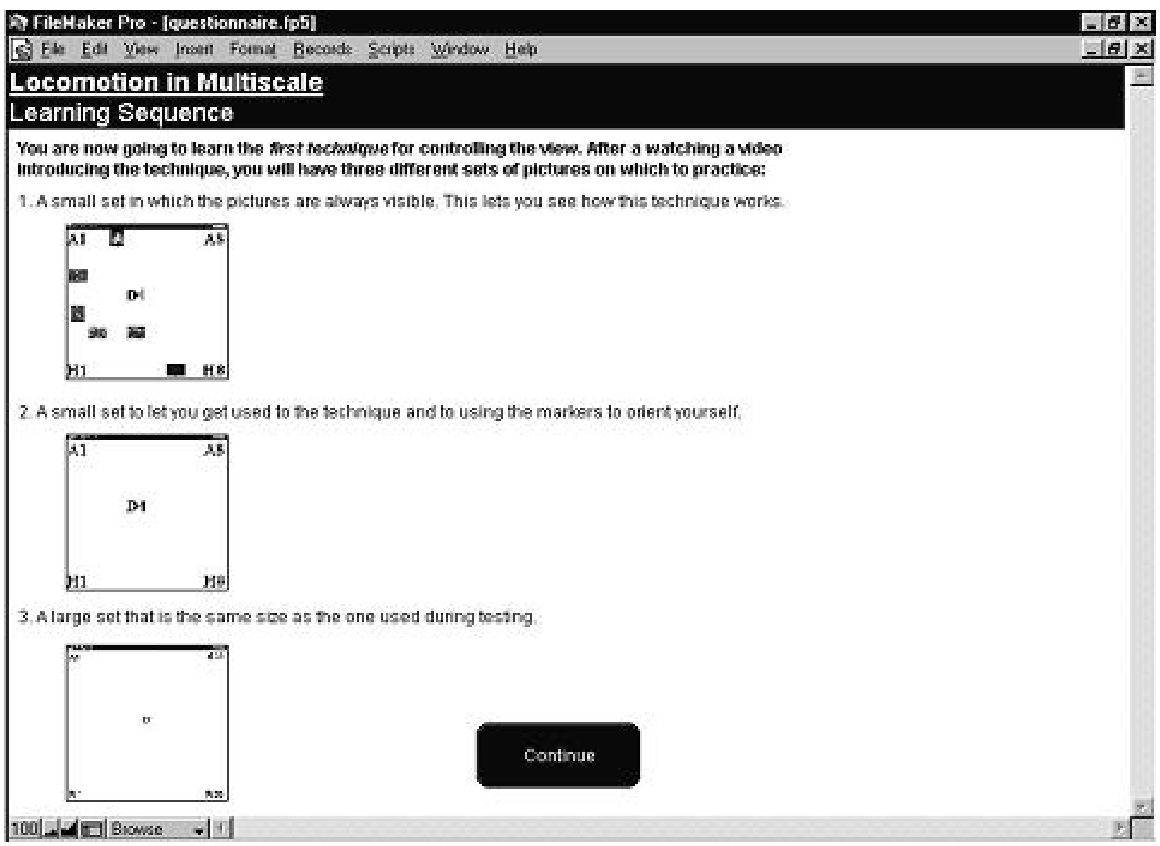
Each video discussed and demonstrated the points shown on the screen, in the order


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Introduction to Experimental Task, Part I
This video will begin to introduce you to the task you will be performing. Please watch it as many times as you like, and feel free to ask any questions you might have.
After watching the video, you may continue when you're ready.
Main Points of the Video
* For the study, a set of pictures have been laid out on the surface.
* Pictures can't be seen until they are larger than two inches.
* Markers provide reference locations for guidance.
* Letters run vertically, numbers horizontally (see guides on monitor)
Press the right arrow to play the video
Continue after watching video
100
Browse



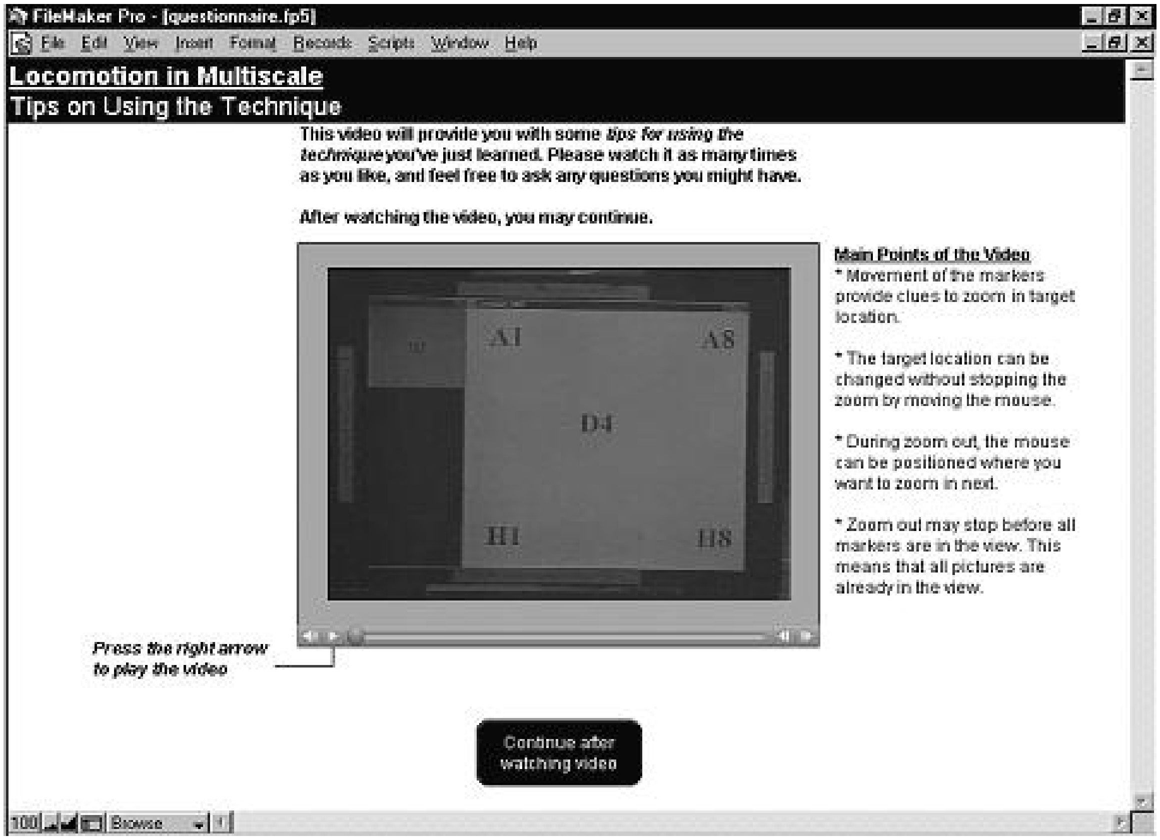
At this point, the researcher asked the subject to point to **H7**, **G4** and **B6**, respectively.


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Introduction to Experimental Task, Part II
This video will finish introducing you to the task. Please watch it as many times as you like, and feel free to ask any questions you might have.
After watching the video, you may continue.
A1
A8
D4
H1
H8
Main Points of the Video
* Prompt window, on the left, tells which picture is to be found.
* Right mouse button zooms in.
* Left mouse button zooms out.
* Press the space bar when the target picture is in the view.
* The picture must be fully in the view.
* Keep one hand on the mouse, the other on the space bar.
Press the right arrow to play the video
Continue after watching video
100
Browse

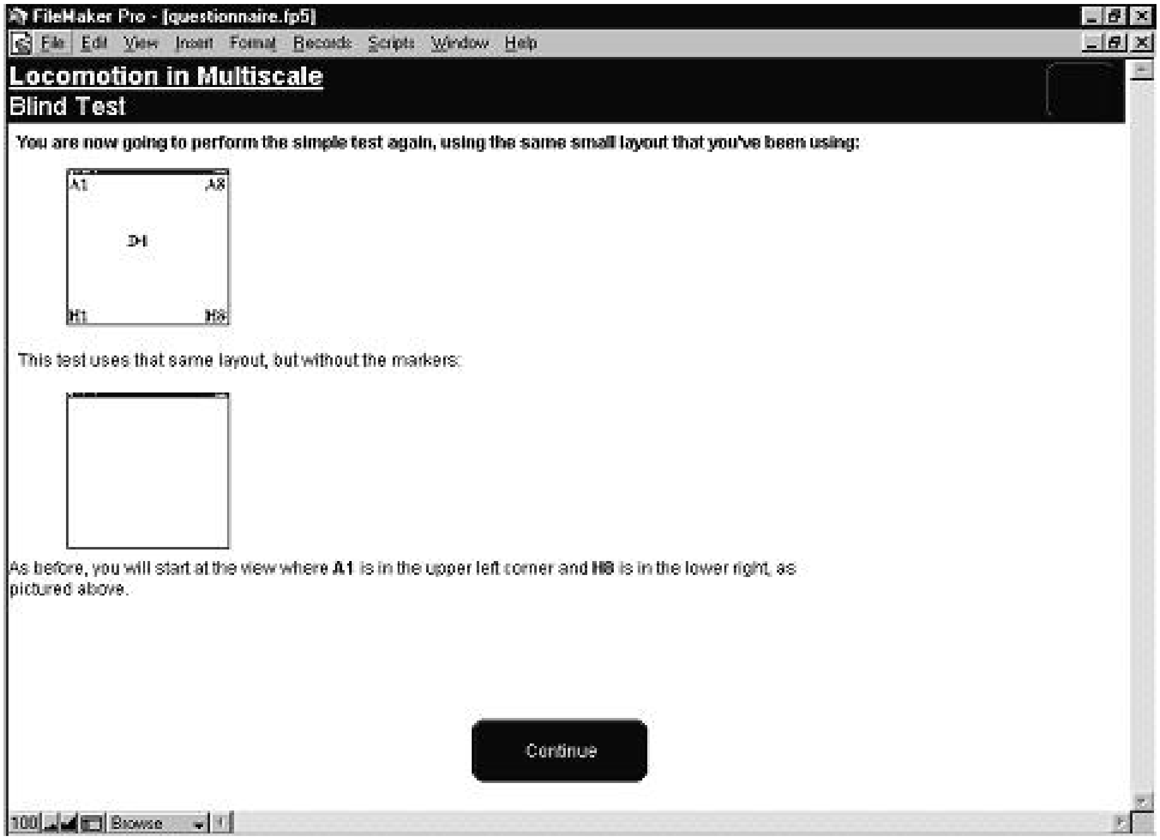

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Learning Sequence
You are now going to learn the first technique for controlling the view. After a watching a video introducing the technique, you will have three different sets of pictures on which to practice:
1. A small set in which the pictures are always visible. This lets you see how this technique works.
A1
A8
D4
H1
H8
2. A small set to let you get used to the technique and to using the markers to orient yourself.
A1
A8
D4
H1
H8
3. A large set that is the same size as the one used during testing.
Continue
100
Browse


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Introduction to Controlling Technique
This video will introduce you to one of two techniques for controlling the view. Please watch it as many times as you like, and feel free to ask any questions you might have.
After watching the video, you may continue.
A1
A8
D4
H1
H8
Main Points of the Video
* Zoom in always moves toward the picture that is closest to the mouse.
* If the mouse moves during zoom in to be closer to another picture, that picture becomes the target of the zoom.
* Zoom out always moves toward the most magnified view that contains all the pictures.
* Mouse location does not matter during zoom out.
* Cursor changes shape to indicate that no further zoom is permitted.
Press the right arrow to play the video
Continue after watching video
100
Browse

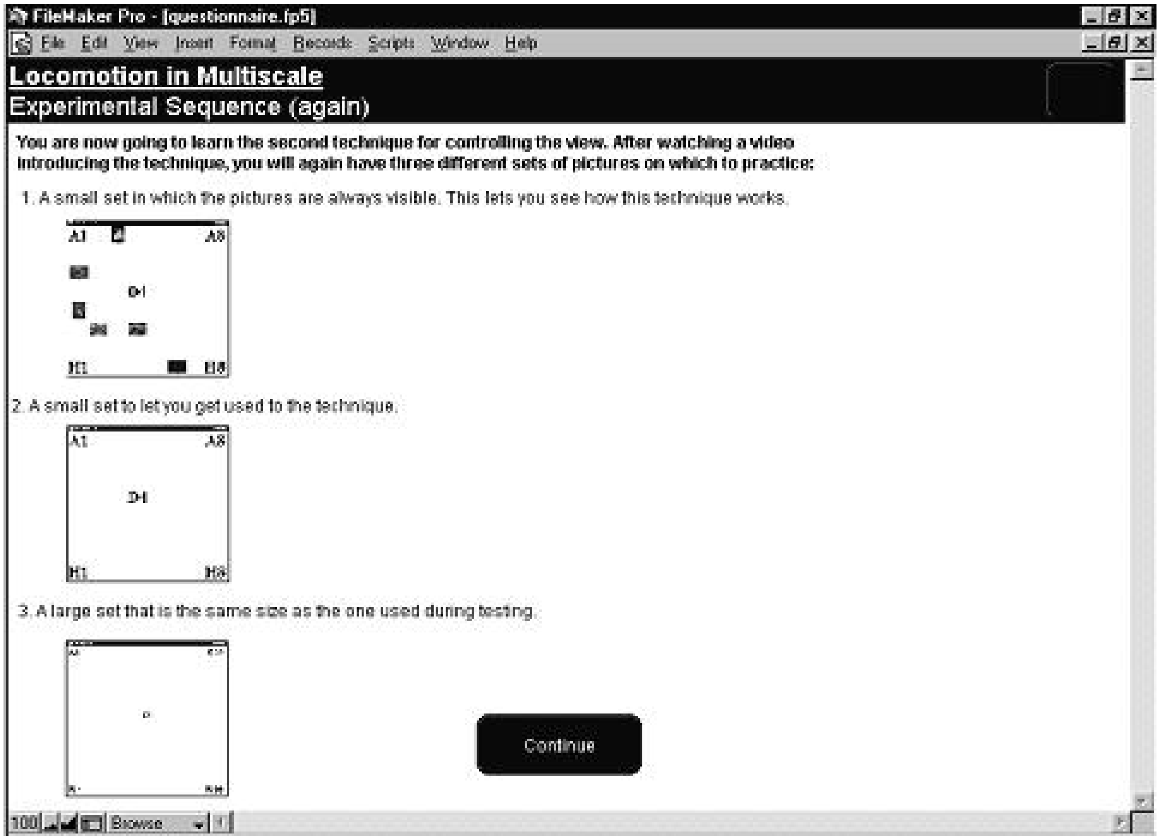
When given this instruction, subjects manually switched to the software that was running in the background.

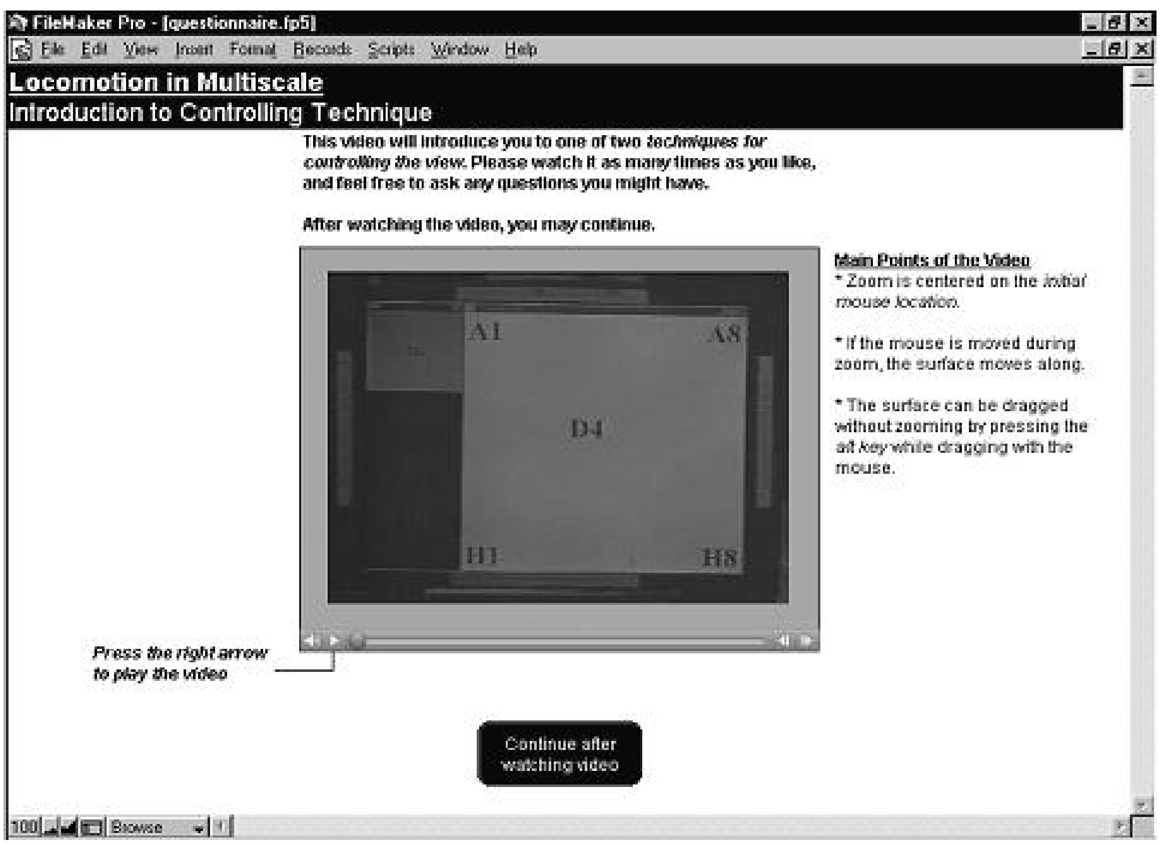

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Tips on Using the Technique
This video will provide you with some tips for using the technique you've just learned. Please watch it as many times as you like, and feel free to ask any questions you might have.
After watching the video, you may continue.
A1
A8
D4
H1
H8
Main Points of the Video
* Movement of the markers provide clues to zoom in target location.
* The target location can be changed without stopping the zoom by moving the mouse.
* During zoom out, the mouse can be positioned where you want to zoom in next.
* Zoom out may stop before all markers are in the view. This means that all pictures are already in the view.
Press the right arrow to play the video
Continue after watching video
100
Browse

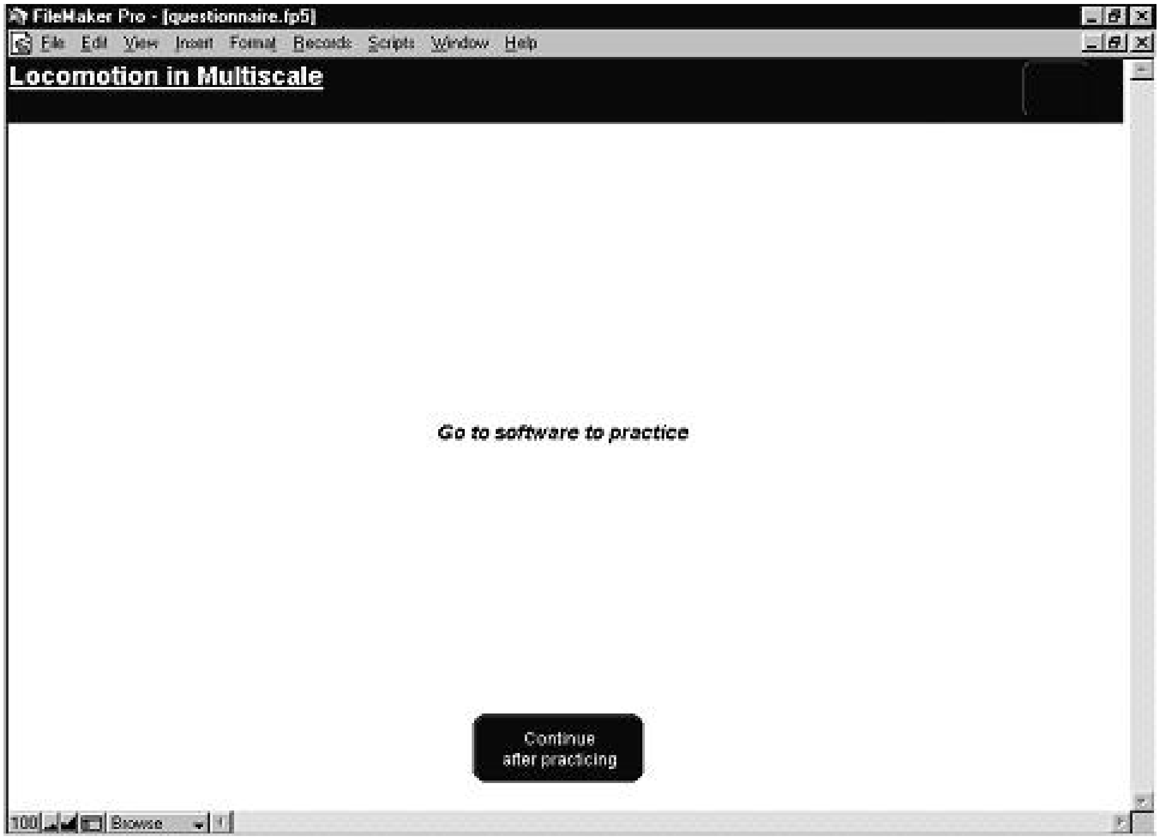

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Go to software for practice and testing
Continue after testing
100
Browse

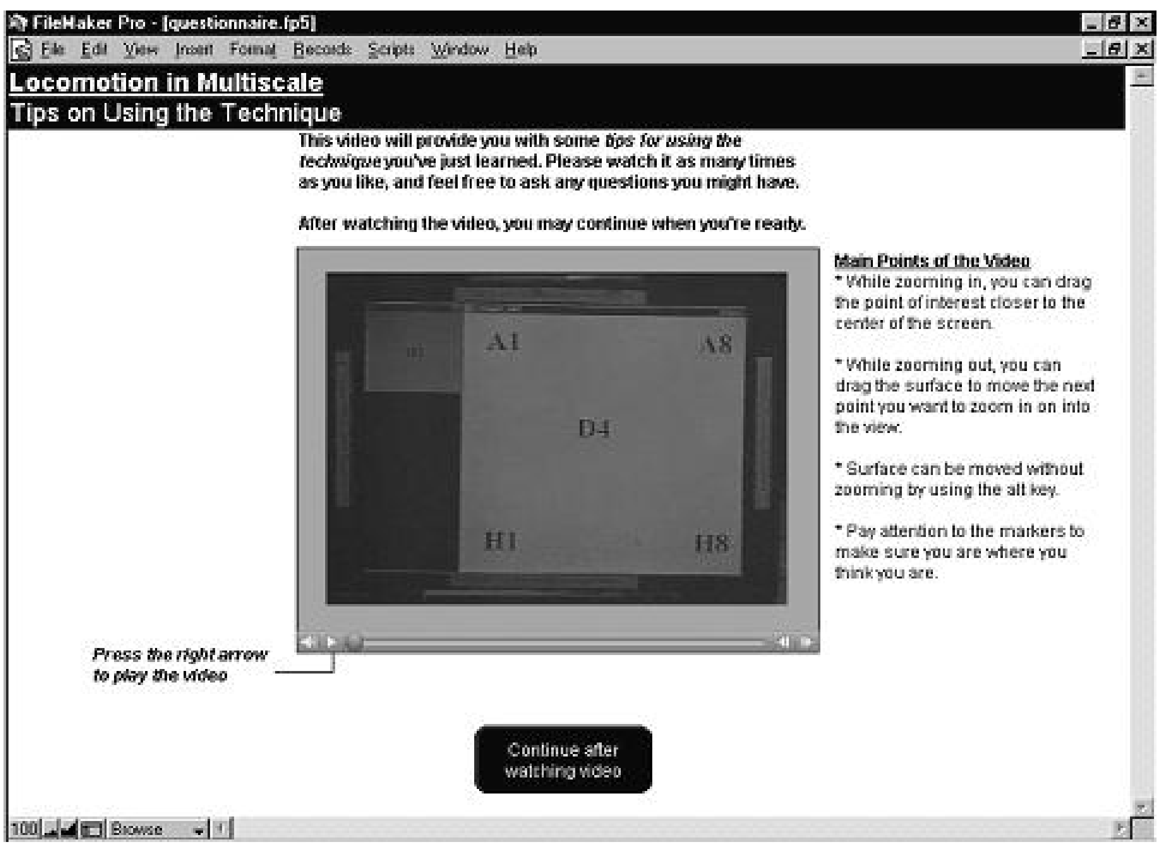

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Blind Test
You are now going to perform the simple test again, using the same small layout that you've been using:
A1
A8
D-I
H1
H8
This test uses that same layout, but without the markers:
As before, you will start at the view where A1 is in the upper left corner and H8 is in the lower right, as pictured above.
Continue
100
Browse

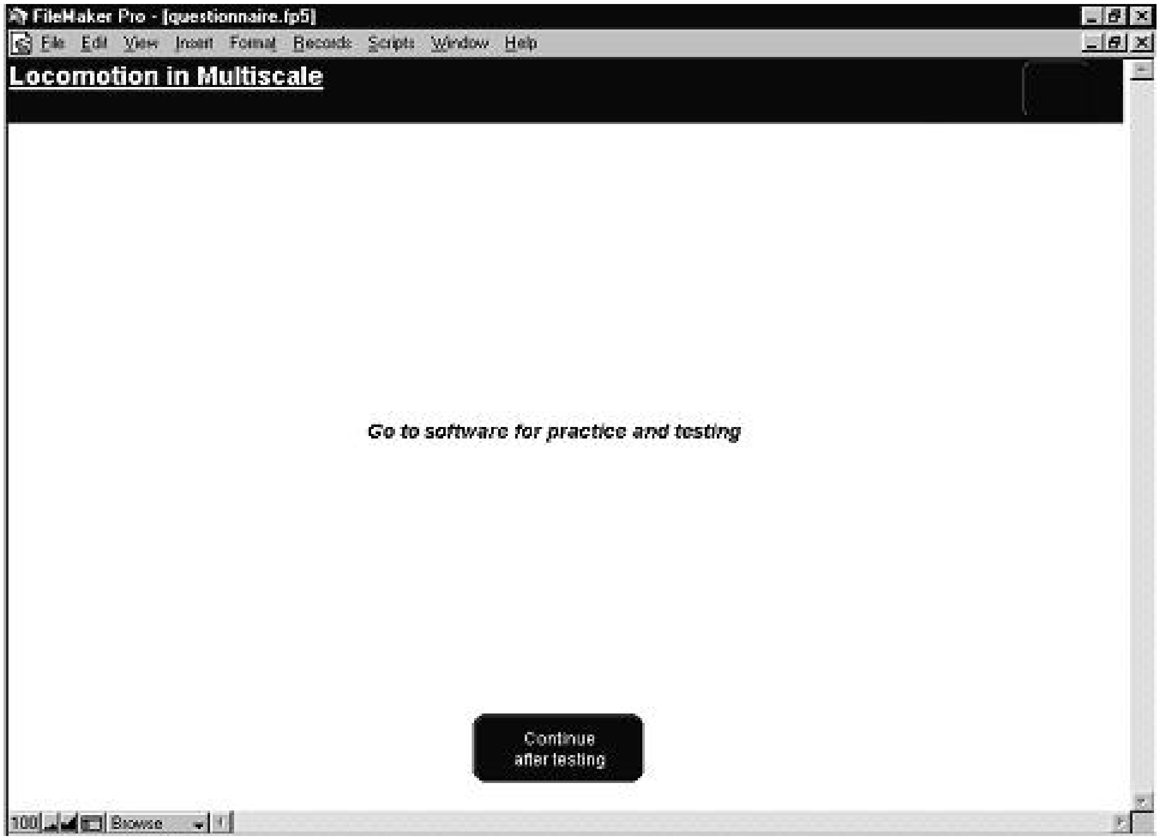

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Go to software for practice and testing
Continue after testing
100
Browse

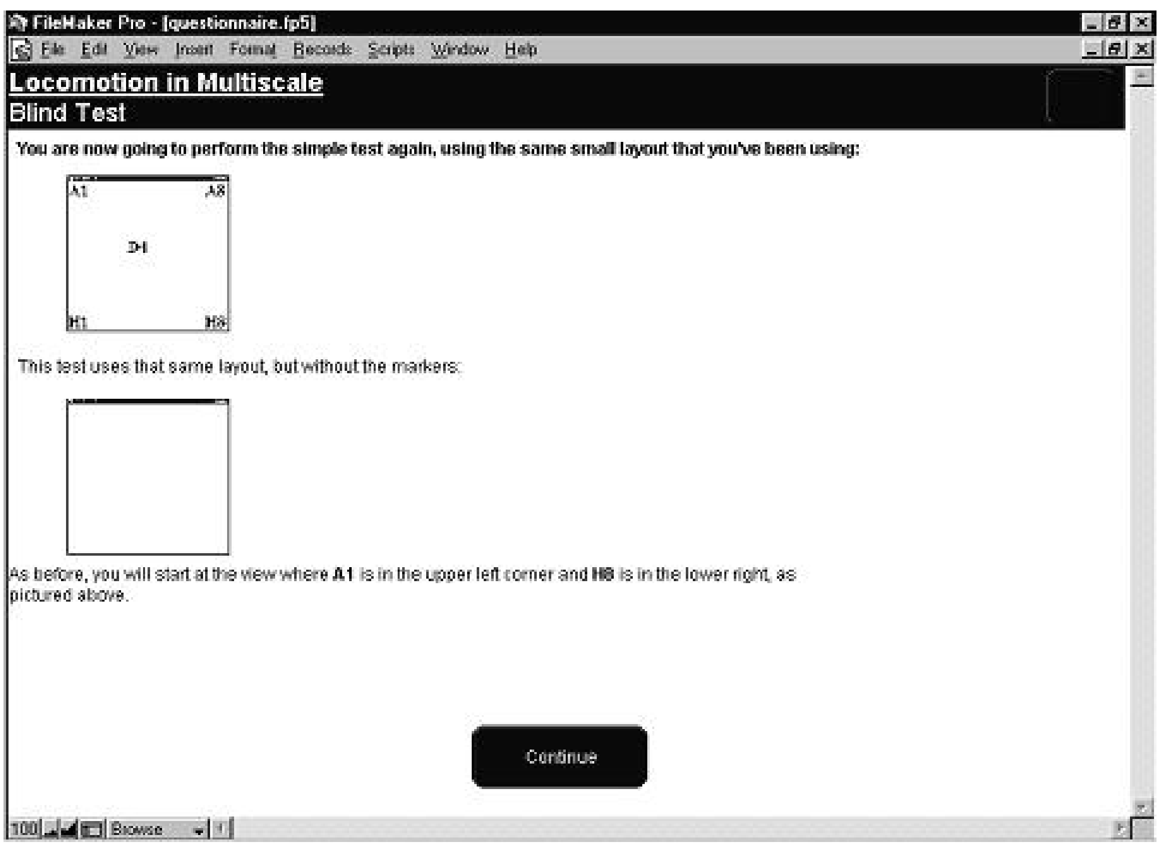

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Experimental Sequence (again)
You are now going to learn the second technique for controlling the view. After watching a video introducing the technique, you will again have three different sets of pictures on which to practice:
1. A small set in which the pictures are always visible. This lets you see how this technique works.
A1
A8
D4
H1
H8
2. A small set to let you get used to the technique.
A1
A8
D4
H1
H8
3. A large set that is the same size as the one used during testing.
Continue
100
Browse

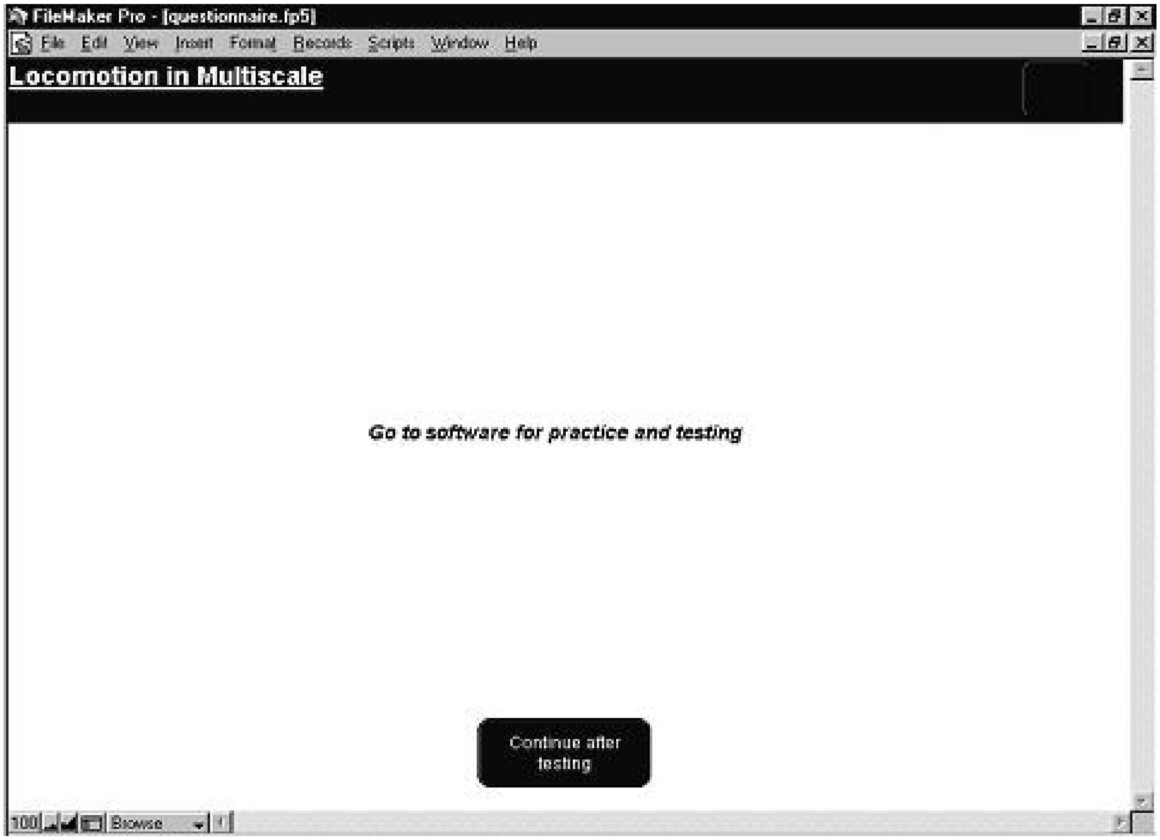

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Introduction to Controlling Technique
This video will introduce you to one of two techniques for controlling the view. Please watch it as many times as you like, and feel free to ask any questions you might have.
After watching the video, you may continue.
A1
A8
D4
H1
H8
Main Points of the Video
* Zoom is centered on the initial mouse location.
* If the mouse is moved during zoom, the surface moves along.
* The surface can be dragged without zooming by pressing the alt key while dragging with the mouse.
Press the right arrow to play the video
Continue after watching video
100
Browse

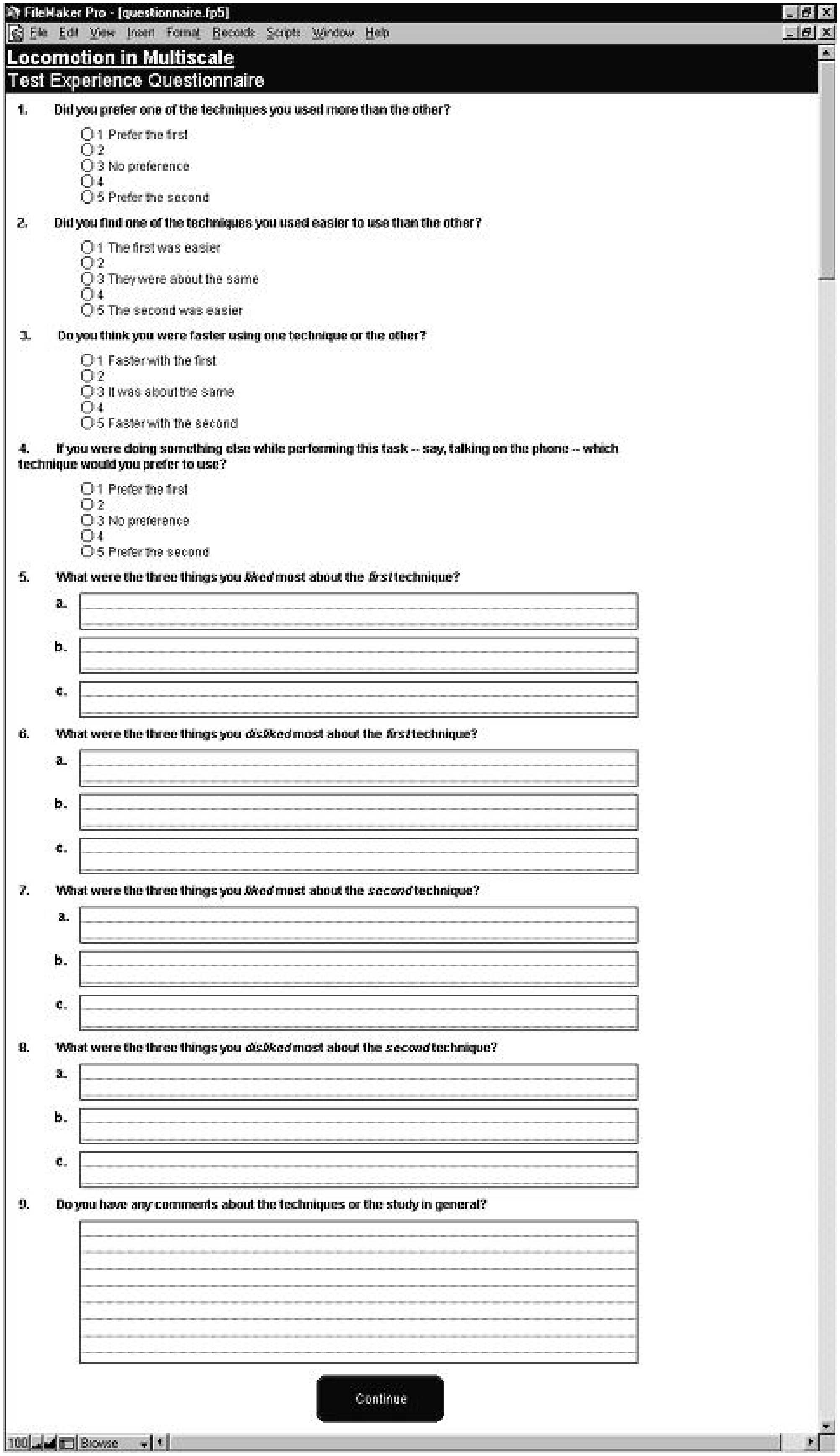

FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Go to software to practice
Continue after practicing
100 Browse


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Tips on Using the Technique
This video will provide you with some tips for using the technique you've just learned. Please watch it as many times as you like, and feel free to ask any questions you might have.
After watching the video, you may continue when you're ready.
A1
A8
D4
H1
H8
Main Points of the Video
* While zooming in, you can drag the point of interest closer to the center of the screen.
* While zooming out, you can drag the surface to move the next point you want to zoom in on into the view.
* Surface can be moved without zooming by using the alt key.
* Pay attention to the markers to make sure you are where you think you are.
Press the right arrow to play the video
Continue after watching video
100 Browse


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Go to software for practice and testing
Continue
after testing
100
Browse


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Blind Test
You are now going to perform the simple test again, using the same small layout that you've been using:
A1
A8
D4
H1
H8
This test uses that same layout, but without the markers:
As before, you will start at the view where A1 is in the upper left corner and H8 is in the lower right, as pictured above.
Continue
100
Browse


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Go to software for practice and testing
Continue after testing
100
Browse



FileMaker Pro - [questionnaire.fp5]

File Edit View Insert Format Records Scripts Window Help

Locomotion in Multiscale

Test Experience Questionnaire

1. Did you prefer one of the techniques you used more than the other?
   - 1 Prefer the first
   - 2
   - 3 No preference
   - 4
   - 5 Prefer the second

2. Did you find one of the techniques you used easier to use than the other?
   - 1 The first was easier
   - 2
   - 3 They were about the same
   - 4
   - 5 The second was easier

3. Do you think you were faster using one technique or the other?
   - 1 Faster with the first
   - 2
   - 3 It was about the same
   - 4
   - 5 Faster with the second

4. If you were doing something else while performing this task -- say, talking on the phone -- which technique would you prefer to use?
   - 1 Prefer the first
   - 2
   - 3 No preference
   - 4
   - 5 Prefer the second

5. What were the three things you *liked* most about the *first* technique?
   a.
   b.
   c.

6. What were the three things you *disliked* most about the *first* technique?
   a.
   b.
   c.

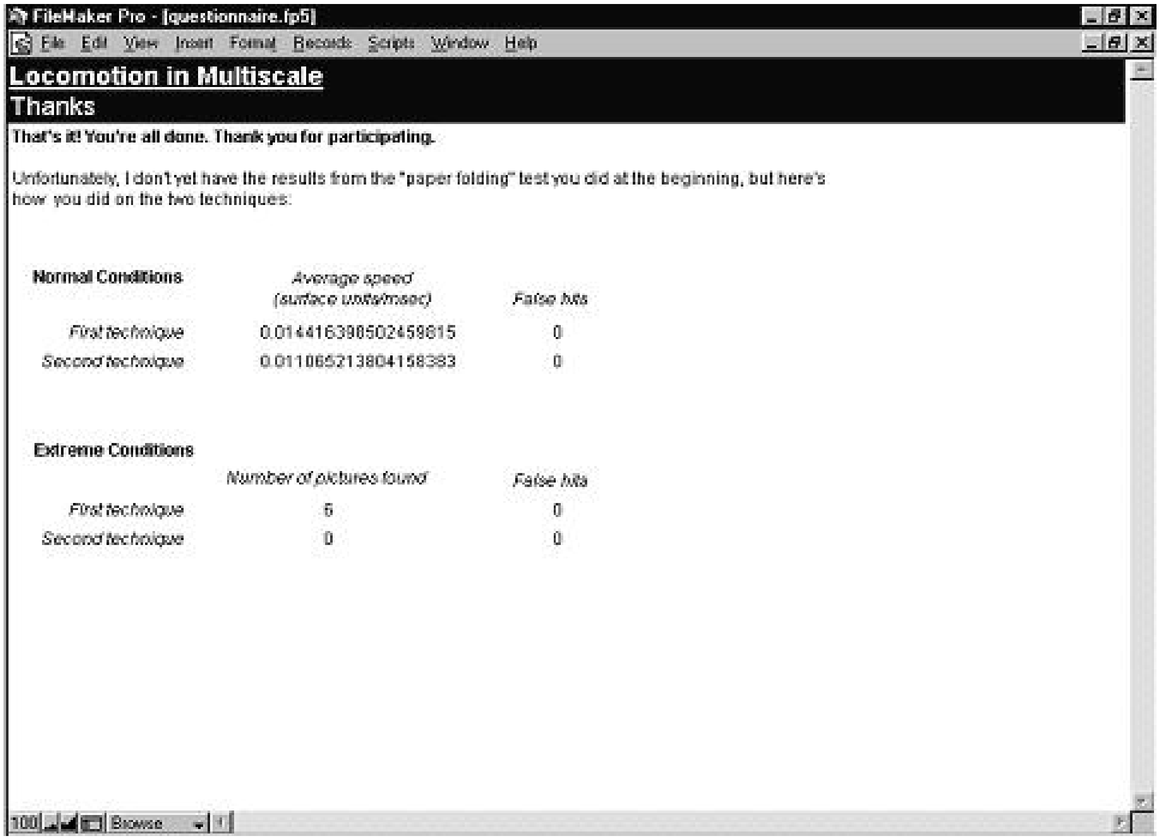
7. What were the three things you *liked* most about the *second* technique?
   a.
   b.
   c.

8. What were the three things you *disliked* most about the *second* technique?
   a.
   b.
   c.

9. Do you have any comments about the techniques or the study in general?

Continue

100 Browse


FileMaker Pro - [questionnaire.fp5]
File Edit View Insert Format Records Scripts Window Help
Locomotion in Multiscale
Thanks
That's it! You're all done. Thank you for participating.
Unfortunately, I don't yet have the results from the "paper folding" test you did at the beginning, but here's how you did on the two techniques:
Normal Conditions
Average speed (surface units/msec)
False hits
First technique
0.014416398502459815
0
Second technique
0.011065213804158383
0
Extreme Conditions
Number of pictures found
False hits
First technique
5
0
Second technique
0
0
100
Browse

APPENDIX G
Subject Consent Forms

LOCOMOTION IN MULTISCALE

Participant Consent Form (General Subject)

If you have any questions or comments about this study, please contact
Susanne Jul at +1 313-617-2345 or SJul@acm.org.

1. **Introduction.** You are invited to participate in a study comparing different techniques for moving in a multiscale environment. With information gathered from you and other participants, we hope to understand how different ways of moving affect the ability to locate and reach objects in electronic environments.
2. **Background Information.** This study is part of the dissertation work of Susanne Jul, a doctoral student in Computer Science and Engineering at the University of Michigan.
3. **Procedures.** If you agree to participate in this study, the researcher will explain the tasks in detail. There will be one session lasting 1½ to 2 hours. In the course of this session you will be introduced to the concept of multiscale, and trained and timed on different movement techniques in an electronic multiscale environment. You will also be asked to fill out some simple questionnaires relating to you and your experience with computers in general and this study in particular.
4. **Risks and Benefits.** This research involves no risks or discomforts greater than those ordinarily encountered in using computers. There are no benefits to participants beyond potential intellectual stimulation and satisfaction from contributing to current research.
5. **Compensation.** You will receive a $25 gift certificate to your choice of Borders Books or Starbucks Coffee as payment for your participation. Legally, you can be paid only if you are a US citizen, a legal resident alien (i.e., possess a "green" card), or have a work eligible visa sponsored by the University of Michigan.
6. **Audiotaping.** The computer screen may be videotaped while you are working. In order to coordinate any comments you make with what is happening on the screen, we would like to record what you say while you are working. This audio recording will be used for illustrative purposes only and is not critical to the results of the study.

   I give consent to be audiotaped during this study (please initial):

   ___ Yes ___ No
7. **Confidentiality.** The records of this study will be kept confidential. No information will be publicly accessible which will possibly identify you as a participant. Your name will not be associated with any of the stored data. The records will be destroyed after a period of not more than five years from the completion of the study.
8. **Subject's Rights.** If you have read this form and have decided to participate in this project, please understand your participation is voluntary and you have the right to withdraw your consent or discontinue participation at any time without penalty. You have the right to refuse to answer particular questions. You may ask questions at any time before, while or after participating. Your individual privacy will be maintained in all published and written data resulting from the study.

   If you have questions about your rights as a study participant, or are dissatisfied at any time with any aspect of this study, you may contact Kate Keever, Administrator, Human Protection Subjects Office, 1040 Fleming Building, University of Michigan 48109, (734) 936-0933, IRB-Behavsci-Health@umich.edu.
9. **Statement of Consent.** I have read this form and voluntarily agree to participate in the study.

______________________________ ______________________________

Participant's Signature Date

You will receive a copy of this form for your records.

LOCOMOTION IN MULTISCALE

Audio Recording Use Consent Form

If you have any questions or comments about this study, please contact
Susanne Jul at +1 313-617-2345 or SJul@acm.org.

As part of this research project, we will be making an audio recording of you while you participate in the experiment. We would like you to indicate what uses of this recording you are willing to allow by initialing below. You are free to initial any number of spaces from none to all of the spaces, and your response will in no way affect your credit for participating. We will only use the recording in ways that you agree to. In any use of this recording, your name would *not* be identified. If you do not initial any of the spaces below, the audio recording will be destroyed. Otherwise, the recording will be destroyed after a period of not more than five years from the completion of the study.

- **The recording can be studied by the research team for use in the research project.**

  Please initial: ____

- **The recording can be used for scientific publications.**

  Please initial: ____

- **The recording can be shown at meetings of scientists interested in the study of emotion.**

  Please initial: ____

- **The recording can be shown in classrooms to students.**

  Please initial: ____

- **The recording can be shown in public presentations to nonscientific groups.**

  Please initial: ____

- **The recording can be used on television and radio.**

  Please initial: ____

I have read the above description and give my consent for the use of the audio recording as indicated above.

______________________________ ______________________

Participant's Signature Date

You will receive a copy of this form for your records.

APPENDIX H

Institutional Review Board Approval for Studies Involving Human Subjects

UNIVERSITY OF MICHIGAN
OFFICE OF THE VICE PRESIDENT FOR RESEARCH
HUMAN SUBJECTS PROTECTION OFFICE
1040 FLEMING ADMINISTRATION BUILDING
ANN ARBOR, MICHIGAN 48109-1340

IRB BEHAVIORAL SCIENCES ~~ APPROVAL NOTICE

APPROVAL DATE: 5/6/01

LENGTH OF APPROVAL: One Year

EXPIRATION DATE 7/6/02

Susanna Jul
400 WEST HALL
Campus 1092

IRB FILE NO: 6367

Dear Ms. Susanna Jul,

The Behavioral Sciences Institutional Review Board (IRB) has approved your proposal:

Evaluating Locomotional Techniques In Multiscale Environments

After careful review of your application, it was determined independently that the rights and welfare of the individual subjects involved in this research are carefully guarded. Furthermore, the methods used to obtain informed consent are appropriate, and the individuals are at no more than minimal risk.

You are reminded of your obligation to advise this IRB office of any change in protocol which might alter your research in a manner that differs from which this approval is based. You are also required to inform the IRB Committee of any and all adverse advents (i.e., injury, emotional upset, fainting). Approval will extend for a period of no more than one year from the approval date listed in this letter. A shorter period may be specified. As the expiration date approaches, you will be reminded to apply for renewal should your data collecting or data analysis be ongoing.

On behalf of the IRB Behavioral Sciences Panel, I wish you success in your research.

Sincerely,

Leonard D. Eron, Chair
Behavioral Sciences Committee IRB

Enclosure: Summary of Investigator's Obligations
cc: DRDA

Source of Funds: NONE

kmk/EXPEDITED

Behavioral Sciences Institutional Review Board 1040 Fleming Administration Building Ann Arbor, MI 48109-1340

INITIAL APPROVAL REQUEST for Studies Involving Human Subjects

UNIVERSITY OF MICHIGAN

IRB Behavioral Sciences Committee

Type all information which you provide. Approval MUST be renewed annually if you continue to gather data. This form is for NEW submissions only. ***IMPORTANT NOTICE:*** *YOU* MUST ***INCLUDE*** the instrument(s) [i.e., survey(s), questionnaire(s), schedule(s)], and consent form(s)]. (Enclose a debriefing form if you will be using the Intro Psych Subject Pool.) **Submit two copies of the completed form, any consent documents, instruments, etc. *** ***Submit 15 copies of each form if your subjects are minors involving more than minimal risk, juveniles in detention centers or prisoners.**** Omission of these items **will delay** the review process.

Principal Investigator: **Susanne Jul**

School/Department: EECS/SI Faculty Advisor's Name: George W. Furnas

Office Address: 406 West Hall Campus Zip: 1092

Home Address: 3800 West Huron River Dr, Ann Arbor MI 49103

Office Phone: Home Phone: E-mail address:

— +1 313-617-2345 sjul@acm.org

Check status: __F_Gender (M or F) _x__Doctoral candidate, ___Faculty, ___Graduate student,

___Post doc ___Research scientist, ___Staff member, ___Undergraduate student

Start Date of Project: **End Date of Project**: Is this work for a course? Which one?

July 23, 2001 Dec 31, 2001 No

DRDA # if known Is this work for your dissertation? Yes___x__ No ______

Contact Person if other than P.I. (i.e., Admin Ass't, Research Ass't, etc.):

Contact Person's E-mail: Contact Person's Phone:

Title of Proposal: Evaluating Locomotional Techniques in Multiscale Environments

Will your subject sample involve UofM students?

If yes, will subjects be obtained from the **Intro Psych Subject Pool**? Yes ____ No__x___

If yes, will subjects be obtained from the **Housing office**: Yes_____

No__x___

If yes, but another source, please explain where: __EECS and SI student mailing lists

Will there be subjects be **under the age of 18**? Yes ____ No __x___

Will **prisoners** or **juveniles in detention centers** be subjects? Yes_____ No__x___

Does this study involve **secondary analysis only**? Yes____ No__x___

If Yes, attach a brief description of study and indicate from which databank the data will be obtained. Can the data be linked? Yes _____ No_____

If proposal has been or will be submitted to an agency, **Agency Name**

Federally **funded**? Yes ___ No _x__ Pending ____ IF YOU ARE AWAITING FUNDING to develop instruments and or consent forms, etc., please check here: ☐

Are there or will there be **other versions** of this proposal submitted to other agencies? Yes ___ No ___

Have these versions been submitted to the IRB for review? Yes ___ No ___ IRB File #

If "no", please submit these. Please ***highlight the sections*** that are different from those in the present application.

Return to: IRB Behavioral Sciences Committee, 1040 Fleming Administration Building, Campus 1340

Rev. 5.01 QUESTIONS? Contact Kate M. Keever by e-mail IRB-Behavsci-Health@umich.edu

See attached *Summary Description*

Subjects will be recruited by e-mail to students (ca. 50 subjects) at the University of Michigan and the Naval Postgraduate School in Monterey CA, as well as a select group of researchers (ca. 25) involved with multiscale research at the University of Maryland and the University of California at San Diego. The study will be carried out at each of these geographic locations.

See attached *Invitation to Participate (General Subjects)* and *Invitation to Participate (Expert Subjects)*

1.Please provide explicit <u>summary description</u> or abstract of your research making sure to address: recruitment and sampling,, interviewing of children, mental or physical stress, risk, invasion of privacy, deception, video/taped recording, protecting identity of subjects, consent, security of data, and other pertinent information. *Use a separate sheet if necessary*. **Please do not attach your proposal.**

---

2. How are the subjects to be recruited for this study? How many subjects you do plan to recruit? From where do you plan to recruit your subjects? Please indicate the location where this study will be conducted. Be sure to specify the exact wording of requests, notices, or advertisements. Attachments of wording or fliers is appropriate.

2a.. How many subjects are expected to be recruited? ________75__________

3. Does this study involve any of the following procedures?

Yes	**No**	
______	___x____	Deception
______	___x____	Punishment
______	___x____	Use of drugs
______	___x____	Covert observation
______	___x____	Interviewing of children (Age range: from ____ to ____)

_______	___x____	Induction of mental and/or physical stress
_______	___x____	Procedures which risk physical harm to the subject
_______	___x____	Materials commonly regarded as socially unacceptable
_______	___x____	Procedures that might be regarded as an invasion or privacy

3A. In the case of any item check "Yes" above, explain the procedure in detail.

3B. Please indicate the theoretical and/or methodological necessity for employing any procedure(s) checked "Yes".

3C. If the study involves deception, when and how will the subjects be debriefed? (Generally, the nature of the deception and its necessity should be explained to the subjects).

4. Will any data be gathered through photographic, video or sound-recording devices?

Yes__x_ No____ If "Yes", how will the confidentiality of the materials produced by such devices be protected? Also, please provide a separate line on the consent form for the subjects to agree to be video/audio taped or photographed.

Audio recordings of subjects will be made in association with video recording of screen activity. There will be no visual recording of subjects.

4A. What will be done with the still photos, video or audio recordings after the study has been collected? Will this information be destroyed, kept *xxx* number of years, used in publication, etc.?

With subjects' consent, audio recordings may be used in interactive presentations containing information about the study. The recordings will not be available publicly and will be destroyed after a period of not more than five years.

5. Will names of subjects be recorded? Yes____ No__x__ (strictly anonymous). If "Yes",answer questions A - D below.

5A. Where will the names be recorded (e.g., on test protocols, on a separate list with code numbers, etc.)?

5B. For what purpose(s) will names be recorded?

5C. Will access to names be under your exclusive control? Yes____ No____ If "No", what will be done to protect the confidentiality of the subjects?

5D. Will names of subjects be included in any publication based on this study?

Yes____ No_____. If "Yes", for what reason(s)?

6. Sometimes research findings are presented in a manner that permits knowledgeable readers to infer the identity of a person used as a subject, even if names are omitted. Do you expect to present findings which may possibly provide such clues?

Yes__x___ No_____. If "Yes", explain.

Audio recordings associated with video clips of screen activity may be used in interactive presentations. It is possible that an audience member would recognize the subject by voice, although it would not be possible to be completely certain of the identification. Any incidental identifying information, e.g., accidental use of names, will be edited from materials used in presentations.

7. Will information be obtained pertaining to persons other than immediate subjects (e.g., their friends)?

Yes_____ No__x___. If "Yes", how will the confidentiality of such persons be protected?

8. If the draft of a consent form is attached which does not fully comply with the instructions, please indicate the nature of and reasons for that discrepancy.

9. Do you intend to obtain written consent? Yes__x___ No _____ If you do not intend to use written consent forms, please answer questions A, B, and C below.

9A. Why do you not intend to use such forms?

9B. In what manner and to what extent would potential subjects be given advance information about the procedure in which they are asked to participate? If using a contact letter, please include it.

9C. In what manner would potential subjects be advised that their participation and continuation in the project would be entirely voluntary? Please provide a copy of the text to be used.

10. If using oral consent, please provide a copy (script) of the text that you will use.

Federal regulations require that we have current consent form(s) being used on file.

Omission of consent form(s) will delay the review process.

This page is to be signed by the principal investigator. If the PI is an undergraduate, graduate student, or doctoral student the faculty supervisor must also sign.

Signature of Principal Investigator Date

NOTE: A research proposal by a graduate or undergraduate student **must** have the following statement signed by a faculty supervisor.

"I have examined this completed form and I am satisfied with the adequacy of the proposed research design and the measures proposed for the protection of human subjects. I will take responsibility for informing the student of the need for the safekeeping of all raw data (e.g., test protocols, tapes, questionnaires, interview notes, etc.) in a University office or computer file."

Print Name and Title of Faculty Supervisor	Signature of Faculty Supervisor
Office Phone	Date

Policy Concerning INFORMED CONSENT

In accordance with Federal regulations, University policy on research involving human subjects requires the use of "informed consent" forms, which must be signed by the subject or the legally authorized representative of the subject. The IRB Behavioral Sciences Committee is charged with the task of reviewing these forms in advance. Therefore, each request for the approval of a research project should be accompanied by a draft copy of a consent form prepared for that project. Only persons whose consent has been obtained in the manner indicated can be used as research subjects. All signed consent forms must be retained by the investigator for a minimum of three years. Only IRB approved consent forms may be used. **If changes are made** to a previously approved consent form, please notify the IRB administrative office. You must have your new consent document reviewed and approved before it may be used for your subjects.

The consent form <u>should not</u> include a waiver of legal rights of the subject or release of others from liability for negligence. **It <u>should</u> include the following**:

a) the **name of the study** as well as the **purpose** of the study;

b) an assurance that participation in the study is the result of a **voluntary** decision by the subject and, if the latter is a minor, by the subject's parent or guardian;

c) an assurance that the subject **may withdraw** from participation at any time without affect to them, the compensation earned before withdrawing, or academic standing or record;

d) a **description of the procedures** in which the subject is asked to participate;

e) information about any possible **discomfort or risk** reasonably to be expected;

f) an estimate of the **length of time** for which the participation of the subject is requested;

g) a statement as to how their **confidentiality** or **anonymity** will be protected; include the statement that “All information collected will remain confidential except as may be required by federal, state or local law.”

h) a statement that **audio/visual recording** devices are being used (if that is the case) and what will be done with the tapes/pictures upon the study's completion (destroyed, erased, archived, kept for future studies, etc). Please provide a separate line on the consent form for the subjects to agree to be video/audio taped or photographed. For example:

Please sign below if you are willing to have this interview recorded on tape (specify audio or video). You may still participate in this study if you are not willing to have the interview recorded.

I am willing to have this interview recorded on tape:

Signed: ____________________________________ Date:________________________

i)information telling the subject what will be done with the **data collected** after the study is completed; and

j)the name, status, and telephone number of the investigator should appear on the consent form. If a researcher is an undergraduate, the name and telephone number of the faculty advisor must also be provided. It is appropriate to include the name, office address, phone number, and e-mail address of the IRB Administrator (Kate M. Keever) on the consent form should the subject have any questions about the study's approval or the research subject's rights..

Questionnaires and Surveys

With respect to **studies which employ questionnaires** as their only source of data, it will be assumed that to answer and return the questionnaire is an appropriate and sufficient expression of free consent, unless there are circumstances (e.g., teacher-student relations between investigator and subject) which cast doubt on this assumption. **However**, a statement should be in written form indicating that the subject is voluntarily completing the form, the length of time expected to complete the form and questions that make them feel uncomfortable may be skipped.

Further Instructions: The committee is authorized to modify the requirement of written consent if information is presented to show that it is not feasible to implement this requirement without jeopardizing a major objective of the proposed study. If you experience difficulty in creating a consent form for your study, please contact the IRB office (734-936-0933) for help. If the attached consent form is a draft, please indicate that and send a copy of the final version to be approved before using it on your subjects.

PLEASE NOTE: All subjects are to be given a copy of the consent document to keep for their records. In that way, if they have questions or need to cancel an appointment, they will have a copy of the consent document for their information.

INITIAL APPROVAL REQUEST for Studies Involving Human Subjects **Susanne Jul**

Evaluating Locomotional Techniques in Multiscale Environments sjul@acm.org

Summary Description

1.Please provide explicit summary description or abstract of your research making sure to address: recruitment and sampling,, interviewing of children, mental or physical stress, risk, invasion of privacy, deception, video/taped recording, protecting identity of subjects, consent, security of data, and other pertinent information. *Use a separate sheet if necessary*. **Please do not attach your proposal.**

Overview: This research is in the area of human-computer interaction, specifically in developing interaction techniques for *zooming user interfaces* (ZUIs). ZUIs are a class of interfaces where interaction is based on altering the magnification (or scale) of views of an electronic environment. To be effective, ZUIs must be coupled with *multiscale environments* in which the information content of objects (and other environmental features) varies with scale. A common problem in such environments is that users are easily lost in scale and are unable to find the desired objects. The present study examines a set of different locomotional techniques—ways of supporting movement—to compare how they differ in supporting wayfinding—the ability to find and get to desired locations.

Protocol: The study consists of a single session lasting 1½ - 2 hours depending on individual subjects' past experience and rate of performance. After briefing on the goals and nature of the study and completion of the written consent forms [see attached], subjects will be asked to complete a brief questionnaire on basic demographics (age, sex, uncorrected impairments to eye-hand coordination), computer experience in general and experience with ZUIs in particular [see attached]. They will then be given a short (ca. 5 min) standard test measuring spatial ability, either part 5 of the *Guilford-Zimmerman Aptitude Survey* or the *University of Santa Barbara Sense-of-Direction Questionnaire* [see attached]. The subject will then be introduced to the concepts of ZUIs and multiscale environments (if necessary). For each of the locomotional techniques examined, the subject will be trained in use of the technique and allowed to practice the experimental task with that technique, then asked to perform the task while data are collected. The experimental task requires the subject to move to a sequence of locations in the multiscale environment by interaction through the mouse [see attached]. After using all techniques, subjects will be asked to complete a brief questionnaire about their experience [see attached]. Subjects will be fully briefed on both the experimental task and the types of data being collected.

Data Collection and Disposition: Three types of data will be collected in the course of computer interaction:

1. Timing and patterns of movement within the environment and of the mouse

2. Video taping of the screen to provide a visual record of the same information

3. Contingent on subjects' written consent: Audio taping of the subject's comments associated with the visual record

Subjects' names will not be associated with any of the recorded data, nor will any of the records be publicly available in any way. All records will be destroyed after a period of not more than five years from the completion of the study.

General Demographics and Computer Experience Questionnaire

This questionnaire is aimed at gathering some simple facts about you and your computer experience.

1. What is your present age?

   18-30

   31-40

   41-50

   51-60

   over 60

2. What sex are you?

   Female

   Male

3. Do you have any *uncorrected* physical impairments that affect your ability to see a normal computer screen or use a mouse or similar input device?

   No

   Yes, specify: Vision impairment Manual dexterity impairment

4. Which hand do you prefer to use when using a computer mouse or similar input device?

   Right

   Left

   Either, I'm completely ambidextrous

5. How often do you use a computer?

   Every day

   A couple of times a week

   A couple of times a month

A couple of times a year

Almost never

6. How long have you been using computers?

Less than a year

1-3 years

3-5 years

6 years or more

7. How long have you been using mouse-based computers?

Less than a year

1-3 years

3-5 years

6 years or more

I don’t use mouse-based computers

8. Have you had any experience with Zooming User Interfaces?

I don't know what a "Zooming User Interface" is

I've seen Jazz, Pad++ or another Zooming User Interface but haven't really used any of them

I've used Jazz or Pad++ some

I've used Jazz or Pad++ extensively, but not recently

I use Jazz regularly

I've used another Zooming User Interface, specify:

9. Do you participate regularly, or have you in the past participated regularly, in activities that require significant navigational or spatial reasoning, such as orienteering, aerobatic flying, cross-country, aerial or marine navigation?

No

Yes, specify:

Guilford-Zimmerman Aptitude Survey (Sample)

The Guilford-Zimmerman Aptitude Survey

Part 5/Spatial Orientation

Name ______________________ Date ________ Score ________ Sex: M F

INSTRUCTIONS.

This is a test of your ability to see changes in direction and position. In each item you are to note how the position of the boat has changed in the second picture from the original position in the first picture.

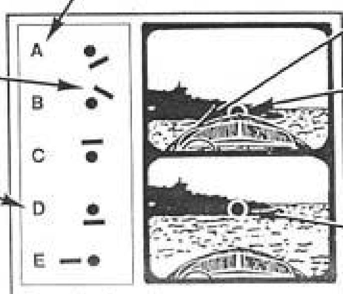
Here is Sample Item 1.

These are the five possible answers to the item.

These bars represent the boat's prow.

This is the correct answer. It shows that the prow of the boat has dropped below the aiming point.

(If the prow had risen, instead of dropped, the correct answer would have been C, instead of D.)



Sample Item 1

This is the prow (front end) of a motor boat in which you are riding.

This is the aiming point. It is the exact spot you would see on land if you sighted right over the point of the prow.

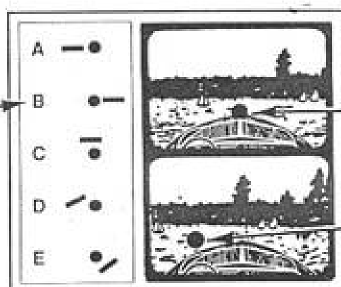
This is the same aiming point shown above. Note that the prow has dropped below it.

To work each item: **First**, look at the top picture and see where the motor boat is headed. **Second**, look at the bottom picture and note the CHANGE in the boat's heading. **Third**, mark the answer that shows the same change on the separate answer sheet.

Try Sample Item 2.

This also shows that the prow of the boat is to the right of the aiming point. So, it is the correct answer.

(If the boat had turned to the left, instead of to the right, the correct answer would have been A.)



Sample Item 2

This is the aiming point.

This is the same aiming point. The motor boat is now headed to the right of it.

Consulting Psychologists Press, Inc., 3803 E. Bayshore Road, Palo Alto, CA 94303

98 97 96 95 94 8 7 6 5 4

0039

UCSB Sense-of-Direction Questionnaire

This questionnaire consists of several statements about your spatial and navigational abilities, preferences, and experience. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Circle "4" if you neither agree nor disagree.

1. I am very good at directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I have a poor memory for where I left things.

strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I am very good at judging distances.

strongly agree 1 2 3 4 5 6 7 strongly disagree

4. My "sense of direction" is very good.

strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W)

strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I get lost very easily in a new city.

strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I enjoy reading maps.

strongly agree 1 2 3 4 5 6 7 strongly disagree

8. I have trouble understanding directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

9. I am very good at reading maps.

strongly agree 1 2 3 4 5 6 7 strongly disagree

10. I don't remember routes very well while riding as a passenger in a car.

strongly agree 1 2 3 4 5 6 7 strongly disagree

11. I don't enjoy giving directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

12. It's not important to me to know where I am.

strongly agree 1 2 3 4 5 6 7 strongly disagree

13. I usually let someone else do the navigational planning for long trips.

strongly agree 1 2 3 4 5 6 7 strongly disagree

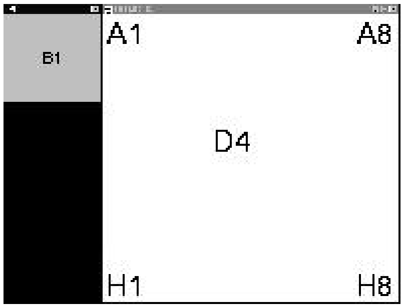
14. I can usually remember a new route after I have traveled it only once.

strongly agree 1 2 3 4 5 6 7 strongly disagree

15. I don't have a very good "mental map" of my environment.

strongly agree 1 2 3 4 5 6 7 strongly disagree

Experimental Task



The target location is presented in the left window (here "B1"). The subject uses the mouse to move to that location, zooming in and out in the right window as needed until the object at that location is visible. The subject indicates that they have reached their destination by pressing the space bar with their non-dominant hand.

Post-Test Questionnaire

1. Did you prefer one of the techniques you used more than the other?

   prefer the first 1 2 3 4 5 prefer the second

2. Did you find one of the techniques you used easier to use than the other?

   the first was easier 1 2 3 4 5 the second was easier

3. Do you think you were faster using one technique or the other?

   faster with the first 1 2 3 4 5 faster with the second

4. If you were doing something else while performing this task—say, talking on the phone—which technique would you prefer to use?

   prefer the first 1 2 3 4 5 prefer the second

5. What were the three things you *liked* most about the *first* technique?
   a.
   b.
   c.
6. What were the three things you *disliked* most about the *first* technique?
   a.
   b.
   c.
7. What were the three things you *liked* most about the *second* technique?
   a.
   b.
   c.
8. What were the three things you *disliked* most about the *second* technique?
   a.

b.

c.

9. Do you have any comments about the techniques or the study in general?

Earn my gratitude and a $25 gift certificate to Borders Books or Starbucks Coffee!

I am a doctoral student studying human-computer interaction [here] at the University of Michigan [visiting the MOVES department]. As part of my dissertation work on supporting navigation in electronic information spaces, I am looking for volunteers to participate in an experimental study. The goal of the study is to examine how different ways of moving in an electronic space affect the user's ability to find objects in the space. In order to participate, you must be able to see sufficiently well to use a visual computer interface and be able to use a mouse or other similar input device. Your participation will consist of a single session lasting one to two hours. During this session you will learn about and get to experiment with a new type of computer interface called a "Zooming User Interface." The session will take place on campus. Along with the opportunity to contribute to science, you will receive a $25 gift certificate to your choice of Borders Books or Starbucks Coffee.

I'll give you a dollar…

I am doing research on navigation in electronic information spaces, and use Jazz (Pad++, earlier) as an experimental platform. As part of my dissertation work at the University of Michigan, I am conducting a study comparing how different ways of moving in Jazz affect the user's ability to find objects on the surface. I am looking for experienced Jazz (or Pad++) users to participate so that I can determine how large an effect experience with thinking in scale might have. Your participation will consist of a single session lasting one to two hours. As a reward for contributing to science, I'll give you a dollar and donate all code to the Jazz community.

I will be in Maryland/San Diego on [tba].

INITIAL APPROVAL REQUEST for Studies Involving Human Subjects **Susanne Jul**

Evaluating Locomotional Techniques in Multiscale Environments sjul@acm.org

Invitation to Participate (Expert Subjects)

APPENDIX I
Copyright Releases

RANDOM HOUSE, INC.

Permissions Department 299 Park Avenue, New York, NY 10171

October 29th, 2002

Susanne Jul
430 Olive Avenue
Palo Alto, CA 94306

Re: OH, THE PLACES YOU'LL GO!; OH, THE THINKS YOU CAN THINK; I HAD TROUBLE IN GETTING TO SOLLA SOLLEW; ON BEYOND ZEBRA! by Dr. Seuss

Dear Ms. Jul:

We have no objection to your use of the above material in your dissertation, as requested in your letter, subject to the following conditions:

1. Such material must be reproduced exactly as it appears in our publication;

2. Full acknowledgment of the title, author, copyright and publisher is given;

3. If your dissertation is ever considered for publication or broadcast, commercially or privately reproduced in any manner not specified in your request, you must reapply for permission.

Best wishes for the success of your paper.

Sincerely,

L. DeMarino

Lorraine DeMarino
Manager, Copyright & Permissions

1

29 October 2002 Our ref: HW/vm/oct02.143

Susanne Jul
University of Michigan

sjul@umich.edu

Dear Ms Jul

HOW DESIGNERS THINK: THE DESIGN PROCESS DEMYSTIFIED, 3RD Edition, 1997, pp 107, Lawson, 1 figure only

As per your letter dated 24 October 2002, we hereby grant you permission to reprint the aforementioned material at no charge **in your thesis** subject to the following conditions:

1. If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies.

2. Suitable acknowledgment to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

   "Reprinted from Publication title, Vol number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier Science".

3. Reproduction of this material is confined to the purpose for which permission is hereby given.

4. This permission is granted for non-exclusive world **English** rights only. For other languages please reapply separately for each one required. Permission excludes use in an electronic form. Should you have a specific electronic project in mind please reapply for permission.

5. This includes permission for UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission.

Yours sincerely

Helen Wilson
Rights Manager

Your future requests will be handled more quickly if you complete the online form at
www.elsevier.com/homepage/guestbook/?form=permis

BIBLIOGRAPHY

Bibliography

There are so many THINKS
that a Thinker can think!
Dr. Seuss, *Oh, the Thinks You Can Think!*[lxvi]

1. Accot, J., Zhai, S. (1997). Beyond Fitts' Law: Models for Trajectory-Based HCI Tasks. *Proceedings of ACM CHI 97 Conference on Human Factors in Computing Systems*, v.1, 295-302.

2. Alexander, C. (1965). A City is Not a Tree. *Architectural Forum*.

3. Anderson, J. R. (1990). *The Adaptive Character of Thought*. Hillsdale, NJ: Lawrence Erlbaum Associates.

4. Annett, J. (2000). Theoretical and Pragmatic Influences on Task Analysis Methods. In Schraagen, J. M., Chipman, S. F., Shalin, V. L. *Cognitive Task Analysis*. Mahwah, NJ: Lawrence Erlbaum Associates. 25-37.

5. Apple Computer Inc. (1992). *Inside MacIntosh: MacIntosh Toolbox Essentials.* Addison-Wesley.

6. *The American Heritage® Dictionary of the English Language, Third Edition.* (1992). Houghton Mifflin Company.

7. Anderson, W. (1985). *The Rise of the Gothic.* Salem, NH: Salem House.

8. Arango, G., Prieto-Dìaz, R. (1991). Part 1: Introduction and Overview: Domain Analysis Concepts and Research Directions. Prieto- Dìaz, R., Arango, G. (Eds.) *Domain Analysis and Software Systems Modeling.* 9-32.

9. Arango, G., Schoen, E., Pettengill, R., Prieto- Dìaz, R., Frakes, W.B. (1993). Design as Evolution and Reuse. *Advances in Software Reuse: Selected Papers from the Second International Workshop on Software Reusability* (Cat. No.93TH0495-2). Los Alamitos, CA, USA: IEEE Comput. Soc. Press. 9-18.

10. Baber, C. (1997). *Beyond the Desktop: Designing and Using Interaction Devices.* San Diego, CA: Academic Press.

[lxvi] [241] Reprinted from *Oh, the Thinks You Can Think!*, Dr. Seuss, p. 22, ©1975, with permission from Random House Publications (Beginner Books).

11. Baecker, R. M., Buxton, W. A. S. (1987). The Haptic Channel (Chapter 8). In Baecker, Ronald M., Buxton, William A. S. (Eds.). *Readings in Human Computer Interaction: A Multidisciplinary Approach.* Los Altos, CA: Morgan Kaufmann Publishers, Inc. 357-365.

12. Bakker, N., Werkhoven, P. J., Passenier, P. O. (1998). Aiding Orientation Performance in Virtual Environments with Proprioceptive Feedback. *Proceedings - Virtual Reality Annual International Symposium 1998*. IEEE Comp Soc, Los Alamitos, CA, USA, 98CB36180, 28-33.

13. Balakrishnan, R., Baudel, T., Kurtenbach, G., Fitzmaurice, G. (1997). The Rockin' Mouse: Integral 3D Manipulation on a Plane. *Proceedings of ACM CHI 97 Conference on Human Factors in Computing Systems*, v.1, 311-318.

14. Ball, L. J., Evans, J., St. B. T., Dennis, I. (1994). Cognitive Processes in Engineering Design: A Longitudinal Study. Special Issue: Cognitive Ergonomics. *Ergonomics,* Vol 37 (11). 1753-1786.

15. Barreau, D., Nardi, B. A. (1995). Finding and Reminding: File Organization from the Desktop. *SIGCHI Bulletin*, Vol.27, No.3 (July).

16. Bartram, L., Henigman, F., Dill, J. (1995). Intelligent Zoom as Metaphor and Navigation Tool in a Multi-Screen Interface for Network Control Systems. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, vol. 4. IEEE, Piscataway, NJ, USA, 95CB35767, 3122-3127.

17. Beach, L. R., Lipshitz, R. (1993). Why Classical Theory is an Inappropriate Standard for Evaluating and Aiding Most Human Decision Making. In Klein, G. A., Orasanu, J., Calderwood, R. Zsambok, C. E. (Eds.) *Decision Making in Action: Models and Methods.* Norwood, NJ: Ablex. 21-35.

18. Beard, D. V., Walker, J. Q. II. (1990.) Navigational Techniques to Improve the Display of Large Two-Dimensional Spaces. *Behaviour & Information Technology*, vol. 9, no. 6, 451-466.

19. Bederson, B. B., Boltman, A. (1999). Does Animation Help Users Build Mental Maps of Spatial Information? In *Proceedings of Information Visualization Symposium* (InfoVis 99). New York: IEEE. 28-35.

20. Bederson, B. B., Hollan, J. D. (1994). Pad++: A Zooming Graphical Interface for Exploring Alternate Interface Physics. *Proceedings of ACM UIST'94,* ACM Press, 17-26.

21. Bederson, B. B., Hollan, J. D. (1995). Pad++: A Zoomable Graphical Interface System. *Human Factors in Computing Systems (CHI) - Conference Proceedings v 2 1995*. New York, NY: ACM Press. 23-24.

22. Bederson B., Meyer J., Good L. (2000). Jazz: An Extensible Zoomable User Interface Graphics Toolkit in Java. *Proceedings of ACM UIST 2000,* ACM Press.

23. Bederson, B. B., Stead, L., Hollan, J. D. (1994). Pad++: Advances in Multiscale Interfaces. *Human Factors in Computing Systems CHI '94 Conference Companion,* New York, NY: ACM Press, 315-316.

24. Bernstein, M. (1988). The Bookmark and the Compass: Orientation Tools for Hypertext Users. *ACM SIGOIS Bulletin*, 9 (4), 34-45.

25. Best, G. A. (1970). Direction-Finding in Large Buildings. In Canter, D. (Ed.), *Architectural Psychology*. London: RIBA Publications, 72-91.

26. Beyer H., Holtzblatt K. (1998). *Contextual Design: Defining Customer-Centered Systems*. Morgan Kaufmann Publishers.

27. Bloom, P., Peterson M. A., Nadel, L., Garrett, M. F. (1996). *Language and Space.* Cambridge, MA: MIT Press.

28. Böök, A., Gärling, T. (1980). Processing of Information about Location during Locomotion: Effects of a Concurrent Task and Locomotion Patterns. *Scandinavian Journal of Psychology*, 21, 185-192.

29. Boyle, C. D. B., Snell, J. R. (1990). Intelligent Navigation for Semistructured Hypertext Documents. In R. McAleese, C. Green (Eds.). *Hypertext: State of the Art*, London: Intellect, 28-42.

30. Brown, P. J. (1989). Do We Need Maps to Navigate Round Hypertext Documents? *Electronic Publishing—Origination, Dissemination and Design*, 2, 91-100.

31. Burns, P. C. (1998). Wayfinding Errors While Driving. *Journal of Environmental Psychology*, Vol 18(2) Jun, 209-217.

32. Butler, K.(1996) . Usability Engineering Turns 10. *interactions*, v3, 1 (Jan.), 59-75.

33. Buxton, W., Hill, R., Rowley, P. (1985). Issues and Techniques in Touch-Sensitive Tablet Input. *Computer Graphics*, 19(3), 215-24.

34. Canon-Bowers, J. A., Bell, H. H. (1997). Training Decision-Makers for Complex Environments: Implications of the Naturalistic Decision Making Perspective. In Zsambok, C. E., Klein, G. (Eds.) *Naturalistic Decision Making.* Mahwah, NJ: Lawrence Erlbaum Associates, 99-110.

35. Canter, D. V. The Place of Architectural Psychology. Honikman, Basil (Ed.). *Proceedings of the Architectural Psychology Conference.* 1970.

36. Canter, D. (1984). Way-finding and Signposting: Penance or Prosthesis? In Easterby, R., Zwaga, H. (Eds.), *Information Design*, Chichester: Wiley, 245-264.

37. Canter, D., Rivers, R., Storrs, G. (1985). Characterizing User Navigation through Complex Data Structures. *Behaviour and Information Technology*, Vol 4(2), (Apr-Jun), 93-102.

38. Card, S. K., English, W. K., Burr, B. J. (1978). Evaluation of Mouse, Rate-Controlled Isometric Joystick, Step Keys and Text Keys for Text Selection on a CRT. Ergonomics, 21(8), 601-613. (Reprinted in Baecker, Ronald M., Buxton, William A. S. (Eds.). (1987). *Readings in Human Computer Interaction: A Multidisciplinary Approach.* Los Altos, CA: Morgan Kaufmann Publishers, Inc.)

39. Card, S. K., Mackinlay, J. D., Robertson, G. G. (1990). The Design Space of Input Devices. *Proceedings of ACM CHI'90, Conference on Human Factors in Computing Systems*, 117-124.

40. Card, S., MacKinlay, J., Shneiderman, B.. (1998). *Readings in Information Visualization: Using Vision to Think*. Morgan Kaufmann Publishers.

41. Card, S., Moran, T. (1986). User Technology: From Pointing to Pondering. *Proceedings ACM Conference on History of Personal Workstations*, 183-198. Reprinted in Baecker, R. M., Buxton, W. A. S. (Eds.). (1995). *Readings in Human Computer Interaction: Toward the Year 2000.* 2nd Ed. San Francisco, CA: Morgan Kaufmann Publishers, Inc., 587-602.

42. Card, S. K., Moran, T. P., Newell, A. (1983). *The Psychology of Human-Computer Interaction.* Hillsdale, NJ: Lawrence Erlbaum Associates.

43. Card, S. K., Robertson, G. G., York, W. (1996). WebBook and the Web Forager: An Information Workspace for the World-Wide Web. *Human Factors in Computing Systems Conference Proceedings CHI 96*, New York, NY: ACM Press, 111-117.

44. Carr, S., Schissler, D. (1969). The City as a Trip: Perceptual Selection and Memory in the View from the Road. *Environment and Behavior*, 1, 7-36.

45. Carroll, J. M. (1995). *Scenario-Based Design: Envisioning Work and Technology in System Development.* John Wiley & Sons, Inc.

46. Chan, C.-S. (1990). Cognitive Processes in Architectural Design Problem Solving. *Design Studies*, Vol. 11, No. 2, April. 60-80.

47. Chance, S. S., Gaunet, F., Beall, A. C., Loomis, J. M. (1998). Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration. *Presence*. Vol. 7, No. 2. April, 168-178.

48. Chen, J.L., Stanney, K.M. (1999). A Theoretical Model of Wayfinding in Virtual Environments: Proposed Strategies for Navigational Aiding. *Presence: Teleoperators and Virtual Environments.* Vol. 8 No. 6. 671-685.

49. Chi, E. H., Pirolli, P., Chen, K., Pitkow, J. (2001). Using Information Scent to Model User Information Needs and Actions and the Web. *Proceedings of ACM CHI 2001 Conference on Human Factors in Computing Systems.* 490-497.

50. Chimera, R., Shneiderman, B. (1994). An Exploratory Evaluation of Three Interfaces for Browsing Large Hierarchical Tables of Contents. *ACM Transactions on Information Systems,* vol. 12 no. 4 (Oct.), 383-406.

51. Chown, E., Kaplan, S., Kortenkamp, D. (1995). Prototypes, Location and Associative Networks (PLAN): Towards a Unified Theory of Cognitive Mapping. *Cognitive Science* 19. 1-51.

52. Christiaans, H. H. C. M., Dorst, K. H. (1992). Cognitive Models in Industrial Design Engineering: A Protocol Study. *Design Theory and Methodology*. American Society of Mechanical Engineers, Design Engineering Division DE v 42. New York, NY, USA: ASME. 131-140.

53. Condoor, S. S., Shankar, S. R., Brock, H. R., Burger, C. P., Jansson, D. G. (1992). Cognitive Framework for the Design Process. *Design Theory and Methodology—DTM '92.* New York, NY, USA: American Society of Mechanical Engineers (ASME), Design Engineering Division. 277-281.

54. Conklin, J. (1987). Hypertext: An Introduction and Survey. *IEEE Computer,* 20, 9, 17-41.

55. Couclelis, H., Golledge, R. G., Gale, N., Tobler, W. (1987). Exploring the Anchorpoint Hypothesis of Spatial Cognition. *Journal of Environmental Psychology,* 7, 99-122.

56. da Silva, D. P., Van Durm, R., Duval, E., Olivie, H.. (1998) Adaptive Navigational Facilities in Educational Hypermedia. *Proceedings of the ACM Conference on Hypertext 1998*. New York, NY, USA: ACM, 291-292.

57. Dada, E.S., Wirasinghe, S.C. (1999). Development of a New Orientation Index for Airport Terminals. *Transportation Research Record.* No. 1662, 41-47.

58. Darken, R. P. (1996). *Wayfinding in Large-Scale Virtual Environments.* PhD Dissertation. School of Engineering and Applied Science. George Washington University.

59. Darken, R. P., Sibert, J. L. (1996). Wayfinding Strategies and Behaviors in Large Virtual Worlds. *Human Factors in Computing Systems Conference Proceedings CHI 96,* New York, NY: ACM Press, 142-149.

60. de Berg, M., van Kreveld, M., Overmars, M., and Schwarzkopf, O. (1997). *Computational Geometry: Algorithms and Applications*. Springer-Verlag.

61. Dill, J., Bartram, L., Ho, A., Henigman, F. (1994). A Continuously Variable Zoom for Navigating Large Hierarchical Networks. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, vol. 1. IEEE, Piscataway, NJ, USA, 94CH3571-5, 386-390.

62. Dillon, A., McKnight, C., Richardson, J. (1993). Space—The Final Chapter or Why Physical Representations Are Not Semantic Intentions. In McKnight, C., Dillon, A., Richardson, J. (Eds.) *Hypertext : A Psychological Perspective*. New York: E. Horwood. 169-191.

63. Dowding, T. J. (1998). *Use of Metacognitive Strategies During Software Navigation*. PhD Dissertation. The University Of Connecticut.

64. Downs, R. M., Stea, D. (1973). Cognitive Maps and Spatial Behaviour: Process and Products. In Downs, R. M., Stea, D. (Eds.) *Image and Environment; Cognitive Mapping and Spatial Behavior.*

65. Drucker, P. F. (1959). *Landmarks of Tomorrow*. New York: Harper.

66. Drucker, P. F. (1967). *The Effective Executive.* New York: Harper & Row.

67. Dyer, F. C. (1998). Cognitive Ecology of Navigation. *Cognitive Ecology: The Evolutionary Ecology of Information Processing and Decision Making.* Chicago, IL, USA: The University of Chicago Press, 201-260.

68. Elliot, R. J., Lesk, M. E. (1982). Route-Finding in Street Maps by Computers and People. *Proceedings American Association of Artificial Intelligence National Conference 1982 (AAAI-82)*. 258-261.

69. Elm, W. C., Woods, D. D. (1985). Getting Lost: A Case Study in Interface Design. *Proc. Human Factors Society 29th Annual Meeting*, 927-931.

70. Elvins, T. T., Nadeau, D. R., Kirsh, D. (1997). Worldlets - 3D Thumbnails for Wayfinding in Virtual Environments. *Proceedings of the ACM Symposium on User Interface Software and Technology - UIST'97*. 21-30.

71. Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors*, 37(1), 32-64.

72. Endsley, M. R. (1997). The Role of Situation Awareness in Naturalistic Decision Making. In Zsambok, C. E., Klein, G. (Eds.) *Naturalistic Decision Making.* Mahwah, NJ: Lawrence Erlbaum Associates, 269-283.

73. Evans, G. W., Skorpanich, M. A., Gärling, T., Bryant, K. J., & Bresolin, B. (1984). The Effects of Pathway Configuration, Landmarks, and Stress on Environmental Cognition. *Journal of Environmental Psychology*, 4, 323-335.

74. Everitt, B. (1980). *Cluster Analysis.* 2nd Ed. New York: Halsted Press.

75. Ferguson, E. L., Hegarty, M. (1994). Properties of Cognitive Maps Constructed from Texts. *Memory & Cognition*, Jul Vol 22(4), 455-473.

76. Fischer, G. (1992). Domain-Oriented Design Environments. *Proceedings of the 7th Knowledge-Based Software Engineering Conference (KBSE'92).*

77. Fischer, G. (1992). Putting the Owners of Problems in Charge with Domain-Oriented Design Environments. In Gilmore, D., Winder, R., Detienne, F. *User-Centered Requirements for Software Engineering Environments.* Heidelberg: Springer Verlag.

78. Foss, C. L. (1989). Tools for Reading and Browsing Hypertext. *Information Processing & Management*, 25 (4), 407-418.

79. Fraser, S., Segel, H., Coplien, J., White, J. (1995). Application of Domain Analysis to Object-Oriented Systems. *OOPS Messenger.* Vol.6, no.4 (Oct.). 46-9.

80. Furnas, G. W. (1995). Effectively View-Navigable Structures. Paper presented at the 1995 Human Computer Interaction Consortium Workshop (HCIC95), Snow Mountain Ranch, Colorado, Feb. 17, 1995. Manuscript available at http://http2.si.umich.edu/~furnas/POSTSCRIPTS/EVN<HCIC95.workshop.paper.ps

81. Furnas, G. W. (1997). Effective View-Navigation. *Human Factors in Computing Systems CHI '97 Conference Proceedings,* New York, NY: ACM Press, 367-374.

82. Furnas, G. W., Bederson, B. B. (1995). Space-Scale Diagrams: Understanding Multiscale Interfaces. *Human Factors in Computing Systems CHI '95 Conference Proceedings*, vol. 1, New York, NY: ACM Press, 234-241.

83. Furnas, G. W., Zhang X. (1998). MuSE: A Multiscale Editor. *Proceedings of the ACM Symposium on User Interface Software and Technology*.107-116.

84. Gale, N., Golledge, R. G., Pellegrino, J. W., Doherty, S. (1990). The Acquisition and Integration of Route Knowledge in an Unfamiliar Neighborhood. *Journal of Environmental Psychology*, 10, 3-25.

85. Galyean, T. A. (1995). Guided Navigation of Virtual Environments. *1995 Symposium on Interactive 3D Graphics.* ACM Press. 103-104.

86. Gärling, T. (1999). Human Information Procesing in Sequential Spatial Choice. In Golledge, R. G. (Ed.). *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes.* Baltimore: The Johns Hopkins University Press. 81-98.

87. Gärling, T., Böök, A., Lindberg, E. (1984). Cognitive Mapping of Large-Scale Environments: The Interrelationship of Action Plans, Acquisition, and Orientation. *Environment and Behavior*, vol. 15, no. 1, Jan, 3-34.

88. Gärling, T., Böök, A., Lindberg, E. (1986). Spatial Orientation and Wayfinding in the Designed Environment: A Conceptual Analysis and Some Suggestions for Postoccupancy Evaluation. *Journal of Architectural & Planning Research,* Feb. Vol. 3(1). 55-64.

89. Gärling, T., Evans, G. (Eds.) (1991). *Environment, Cognition, and Action: An Integrated Approach.* New York, NY, USA: Oxford University Press.

90. Gärling, T., Golledge, R. G. (1987). Environmental Perception and Cognition. In Zube, E. H., Moore, Gary T. (Eds.) *Advances in Environment, Behavior and Design*, Vol. 2. New York: Plenum Press. 203-236.

91. Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

92. Gladwin, T. (1970). *East is a Big Bird; Navigation and Logic on Puluwat Atoll.* Cambridge, MA: Harvard University Press.

93. Goble, C., Harper, S., Stevens, R. (2000). Travails Of Visually Impaired Web Travellers. *Proceedings of the ACM Conference on Hypertext.* New York, NY, USA: ACM, 1-10.

94. Goel, V. A. (1994). Comparison of Design and Nondesign Problem Spaces. *Artificial Intelligence in Engineering*, v 9 n 1. 53-72.

95. Goel, V., Pirolli, P. (1992). The Structure of Design Problem Spaces. *Cognitive Science.* Jul-Sep Vol 16(3), 395-429.

96. Golledge, R. G. (1993). Geographical Perspectives on Spatial Cognition. In Görling, T. & Golledge, R. G. (Eds.*) Behavior and Environment: Psychological and Geographical Approaches.* Amsterdam: North-Holland. 170-192.

97. Golledge, R. G. (1999). Human Wayfinding and Cognitive Maps. In Golledge, R. G. (Ed.). *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes.* Baltimore: The Johns Hopkins University Press. 5-45.

98. Golledge, R. G., Smith, T. R., Pellegrino, J. W., Marshall, S. P., Doherty, S. (1985). A Conceptual Model and Empirical Analysis of Children's Acquisition of Spatial Knowledge. *Journal of Environmental Psychology*, 5. 125-152.

99. Gopal, S., Smith, T. R. (1990). Human Way-Finding in an Urban Environment: A Performance Analysis of A Computational Process Model. *Environment and Planning A*, v. 22. 169-191.

100. Greeno, J. G. Nature of Problem-Solving Abilities. (1978). In Estes, W. K. (Ed.) Handbook of Learning and Cognitive Processes: V. Human Information Processing. Hillsdale, NJ: Lawrence Erlbaum.

101. Gross, M. D., Zimring, C. (1992). Predicting Wayfinding Behavior in Buildings: A Schema-Based Approach. In Kalay, Y. E. (Ed.) *Evaluating and Predicting Design Performance*. New York, NY: Wiley and Sons.

102. Hackos, J. T., Redish, J. C. (1998). *User and Task Analysis for Interface Design*. John Wiley & Sons.

103. Halasz, F. (1988). Reflections on Notecards: Seven Issues for the Next Generation of Hypermedia Systems. Comm. ACM (July) 31, 7, 836-861.

104. Hanson, A. J., Wernert, E. A., Hughes, S. B. (1999). Constrained navigation environments. In Hans Hagen, Gregory M. Nielson, and Frits Post, (eds.), *Scientific Visualization: Dagstuhl '97 Proceedings*, IEEE Computer Society Press. 95-104.

105. Harnad, S. (1987). Category Induction and Representation. In Harnad, S. (ed.). *Categorical Perception: The Groundwork of Cognition*. New York: Cambridge University Press.

106. Harris, L., Jenkin, M., Zikovitz, D. C. (1999). Vestibular Cues and Virtual Environments: Choosing the Magnitude of the Vestibular Cue. *Proceedings - Virtual Reality Annual International Symposium 1999*, 229-236.

107. Hart, Roger A., Moore, Gary T. (1973.) The Development of Spatial Cognition: A Review. In Downs, R. M., Stea, D. (Eds.) *Image and Environment; Cognitive Mapping and Spatial Behavior.* 246-288.

108. Haspelmath, M. (1997). *From Space to Time: Temporal Adverbials in the World's Languages.* Munchen: LINCOM Europa.

109. Heft, H. (1979). The Role of Environmental Features in Route-Learning: Two Exploratory Studies of Way-Finding. *Environmental Psychology and Nonverbal Behavior*, 3, 172-185.

110. Henderson, D. A., Jr., Card, S. A. (1985). The Use of Multiple Virtual Workspaces to Reduce Space Contention in a Window-Based Graphical User Interface. *ACM Transactions on Graphics*, v.5 n.3. 211-243.

111. Hill, W. C., Hollan, J. D., Wroblewski, D., McCandless, T. (1992). Edit Wear and Read Wear. *ACM Conference on Human Factors in Computing Systems - CHI '92*, p. 3 – 9. New York: ACM.

112. http://www-3.ibm.com/ibm/easy/eou_ext.nsf/publish/558

113. http://www-library.itsi.disa.mil/tafim/tafim3.0/pages/volume8/frontmtr.htm

114. http://www.sjul.org/jazz

115. http://www.southbend.tech.purdue.edu/arthistory/Glossary/glossary_defg.htm

116. http://www.umd.edu/hcil/jazz

117. Hinckley, K., Pausch, R., Goble, J. C., Kassel, N. F. (1994). A Survey of Design Issues in Spatial Input. *Seventh Annual Symposium on User Interface Software and Technology*, 213-222.

118. Hirtle, S. C., Heidorn, P. B. (1993). The Structure of Cognitive Maps: Representations and Processes. In Görling, T. & Golledge, R. G. (Eds.) *Behavior and Environment: Psychological and Geographical Approaches.* Amsterdam: North-Holland. 170-192.

119. Hirtle, S. C., Jonides, J. (1985). Evidence of Hierarchies in Cognitive Maps. *Memory & Cognition*, 13(3), 208-271.

120. Hirtle, S. C., Mascolo, M. F. (1986). Effect of Semantic Clustering on the Memory of Spatial Locations. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 12, 182-189.

121. Hofmann, M., Langendorfer, H., Laue, K., Lubben, E. (1991). The Principle of Locality Used for Hypertext Presentation: Navigation and Browsing in CONCORDE. *Proc. of the HCI '91 Conference.* British Computer Society Conference Series. Diaper, D. Hammond, N. (Eds.) Cambridge: Cambridge University Press.

122. Höök, K., Benyon, D., Dahlbäck, N., McCall, R., Macaulay, C., Munro, A., Persson, P., Sjölinder, M., Svensson, M. (1998). Introduction: A Framework for Information Space, Personal and Social Navigation. In Dahlbäck, N (Ed.) *Exploring Navigation: Towards a Framework for Design and Evaluation of Navigation in Electronic Spaces.* Technical Report SICS T98.01. Swedish Institute of Computer Science. 1-12.

123. Hovestadt, V., Gramberg, O., Deussen, O. (1995). Hyperbolic User Interfaces for Computer Aided Architectural Design. *Human Factors in Computing Systems (CHI) - Conference Proceedings*, v 2. 304-305.

124. Hutchins, E. (1994). *Cognition in the Wild*. MIT Press. 1994.

125. Igarashi, T., Hinckley, K. (2000). Speed-Dependent Automatic Zooming for Browsing Large Documents. *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology*, 139-148.

126. Igarashi, T., Kadobayashi, R., Mase, K., Tanaka, H. (1998). Path Drawing for 3D Walkthrough. *Proceedings of the 11th Annual ACM Symposium on User Interface Software and Technology, UIST 98*, 173-174.

127. Ingram, R., Benford, S. (1995). Legibility Enhancement for Information Visualisation. *Proceedings of IEEE Visualization '95.* 209-216.

128. Isaak, M. I., Just, M. A. (1995). Constraints on Thinking in Insight and Invention. In Sternberg, R. J., Davidson, J. E. (Eds.) *The Nature of Insight.* Cambridge, MA: MIT Press. 281-325.

129. Jacob, R. J. K., Leggett, J. J., Myers, B. A., Pausch, R. (1993). Interaction Styles and Input/Output Devices. *Behaviour and Information Technology*, 12(2), 69-79.

130. Jackendoff, R. (1983). *Semantics and Cognition.* Cambridge, MA: MIT Press.

131. Jellinek, H. D., Card, S. K. (1990). Powermice and User Performance. *Proceedings of ACM CHI'90 Conference on Human Factors in Computing Systems*, 213-220.

132. John, B. E., Kieras, D. E. (1996). The GOMS Family of User Interface Analysis Techniques: Comparison and Contrast. *ACM Transactions on Computer-Human Interaction*, v.3 n.4. 320-351.

133. Johnson, J. (2000). *GUI Bloopers: Don’ts and Do’s for Software Developers and Web Designers.* San Francisco, CA: Morgan Kaufmann Publishers.

134. Johnson, J., Roberts, T. L., Verplank, W., Smith, D. C., Irby, C. H., Beard, M. Mackey, K. (1989). The Xerox Star: A Retrospective. *IEEE Computer,* Sep. Reprinted in Baecker, R. M., Buxton, W. A. S. (Eds.). (1995). *Readings in Human Computer Interaction: Toward the Year 2000.* 2nd Ed. San Francisco, CA: Morgan Kaufmann Publishers, Inc.

135. Judd, S. P. D., Dale, K., Collett, T. S. (1999). On the Fine Structure of View-Based Navigation in Insects. In Golledge, R. G. (1999). *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes.* Johns Hopkins University Press, 229-258.

136. Jul, S. (2002). Predictive Targeted Movement in Electronic Spaces. *ACM Conference on Human-Factors in Computing Systems, CHI 2002.*

137. Jul, S., Furnas, G. W. (1997). Navigation in Electronic Worlds. *SIGCHI Bulletin*, 29, 4 (Oct), 44-49.

138. Jul, S., Furnas, G. W. (1998). Critical Zones in Desert Fog: Aids to Multiscale Navigation. *ACM Symposium on User Interface Software and Technology, UIST 98,* 97-107.

139. Kang, S. B. (1998). Hands-Free Navigation in VR Environments by Tracking the Head. *International Journal of Human-Computer Studies*, Vol 48(2) Feb, 247-266.

140. Kaplan, S. (1973) . Cognitive Maps in Perception and Thought. In Downs, R. M., Stea, D. (Eds.) *Image and Environment; Cognitive Mapping and Spatial Behavior.*

141. Kaplan, S. (1976). Adaptation, Structure, and Knowledge. In Moore, G., Golledge, R. (Eds.). *Environmental Knowing*. Stroudsburg, PA: Dowden, Hutchinson and Ross. 32-45.

142. Keenan, S. L., Hartson, H. R., Kafura, D. G., Schulman, R. S. (1999). The Usability Problem Taxonomy: A Framework for Classification and Analysis. *Empirical Software Engineering.* Vol.4, no.1 (March). 71-104.

143. Kerr, S. T. (1990). Wayfinding in an Electronic Database: The Relative Importance of Navigational Cues vs. Mental Models. *Information Processing and Management*, Vol. 26, No. 4., 511-523.

144. Kidd, A. (1994). The Marks are on the Knowledge Worker. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. 186 - 191.

145. Klein, G. (1997). The Recognition-Primed Decision (RPD) Model: Looking Back, Looking Forward. In Zsambok, C. E., Klein, G. (Eds.) *Naturalistic Decision Making.* Mahwah, NJ: Lawrence Erlbaum Associates, 285-292.

146. Klein, G. (1998). *Sources of Power: How People Make Decisions.* Cambridge, MA: MIT Press.

147. Klein, G. A., Orasanu, J., Calderwood, R., Zsambok, C. E. (1993). *Decision Making in Action: Models and Methods.* Norwood, NJ: Ablex.]

148. Klein, W. (1983). Deixis and Spatial Orientation in Route Directions. In Pick, H. L., Jr., Acredolo, L. P. (Eds.) *Spatial Orientation: Theory, Research, and Application.* New York : Plenum Press, 283-311.

149. Koffka, K. (1935). *Principles of Gestalt Psychology*. London: Lund Humphries.

150. Kolb, D. (1984). *Experiential Learning*, Englewood Cliffs, NJ: Prentice Hall.

151. Kroemer, Karl, H. E. (1986). Coupling the Hand with the Handle: An Improved Notation of Touch, Grip, and Grasp. *Human Factors*, 28(3), 337-339.

152. Kuipers, B. (1983). The Cognitive Map: Could it Have Been Any Other Way?. In Pick, H. L., Jr., Acredolo, L. P. (Eds.). *Spatial Orientation: Theory, Research, and Application*. New York : Plenum Press, 345-359.

153. Kuipers, B. (1990). Commonsense Knowledge of Space: Learning from Experience. Chen, Su-shing. (Ed.) In *Advances in Visuospatial Resoning*. Vol 2. Ablex Publishing Corp. 199-206.

154. Kuipers, B. (1990). Modeling Spatial Knowledge. Chen, Su-shing. (Ed.) In *Advances in Visuospatial Resoning*. Vol 2. Ablex Publishing Corp. 171-198.

155. Kuipers, B. (2000). The Spatial Semantic Hierarchy. *Artificial Intelligence*, v 119 n 1. 191-233.

156. Kuipers, B. J., Levitt, T. S. (1988) Navigation and Mapping in Large-Scale Space. *AI Magazine*, 9 (2), 25-43.

157. Kullberg, R. L. (1995). Dynamic Timelines Visualizing the History of Photography. *Human Factors in Computing Systems Conference Companion CHI 96,* New York, NY: ACM Press, 386-387.

158. Kyselka, W. (1987). *An Ocean in Mind,* University of Hawaii Press.

159. Larman, C. (2002). *Applying UML and Patterns*. Upper Saddle River, NJ: Prentice-Hall, Inc.

160. Lawson, B. (1994). *Design in Mind.* Oxford: Butterworth Architecture.

161. Lawson, B. (1997). *How Designers Think.* 3rd ed. Architectural Press.

162. Lawson, B. (2001). *The Language of Space.* Oxford; Boston: Architectural Press.

163. Lawson, B. R. (1979). Cognitive Strategies in Architectural Design. *Ergonomics*, Vol. 22, no. 1 (Jan). 59-68.

164. Lawton, C. A. (1994). Gender Differences in Way-Finding Strategies: Relationship to Spatial Ability and Spatial Anxiety. *Sex Roles*, Jun Vol 30(11-12), 765-779.

165. Levinson, S. C. (2003). *Space in Language and Cognition: Explorations in Cognitive Diversity.* Cambridge, UK: Cambridge University Press.

166. Lieberman, H. (1994). Powers of Ten Thousand: Navigating in Large Information Spaces. *Proceedings of the ACM Symposium on User Interface Software and Technology*. ACM Press. 15-16.

167. Linard, M., Zeiliger, R. (1995). Designing Navigational Support for Educational Software. *EWHCI '95*. 130-145.

168. Lindberg, E., Gärling, T. (1981).Acquisition of Locational Information About Reference Points During Blindfolded and Sighted Locomotion: Effects of a Concurrent Task and Locomotion Paths. *Scandinavian Journal of Psychology,* 22, 101-108.

169. Lindberg, E., Gärling, T. (1982). Acquisition of locational information about reference points during locomotion: The role of central information processing. *Scandinavian Journal of Psychology*, 23, 207-218.

170. Lipshitz, R., Shaul, O. B. (1997). Schemata and Mental Models in Recognition-Primed Decision-Making. In Zsambok, C. E., Klein, G. (Eds.) *Naturalistic Decision Making.* Mahwah, NJ: Lawrence Erlbaum Associates, 293-303.

171. Lloyd, P., Scott, P. (1994). Discovering the Design Problem. *Design Studies*, Vol. 15, No. 2, (April). 125-140.

172. Lynch, K (1960.) *The Image of the City*. MIT Press.

173. Loomis, J. M., Klatzky, R., L., Golledge, R. G., Philbeck, J. W. (1999). Human Navigation by Path Integration. In Golledge, R. G. (1999). *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. Johns Hopkins University Press, 125-151.

174. Løvås, Gunnar G. (1998). Models of Wayfinding in Emergency Evacuations. *European Journal of Operational Research*, v 105 n 3 Mar 16, 371-389.

175. Mackenzie, I. S. (1992). Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *Human-Computer Interaction*, v.7 n.1, 91-139.

176. MacKenzie, I. S., Soukoreff, R. W., Pal, C. (1997). A Two-Ball Mouse Affords Three Degrees of Freedom. *Proceedings of ACM CHI 97 Conference on Human Factors in Computing Systems,* v.2, 303-304.

177. Mackinlay, J. D., Card, S. K., Robertson, G. G. (1990). Rapid Controlled Movement Through a Virtual 3D Workspace. *SIGGRAPH '90 Conference Proceedings,* in *Computer Graphics* 24 (4, Aug.), 171-176.

178. Mackinlay, J. D., Card, S. K., Robertson, G. G. (1990). A Semantic Analysis of the Design Space of Input Devices. *Human-Computer Interaction*, v.5 n.2-3, 145-190.

179. MacLean, A., Young, R. M., Bellotti, V. M. E., Moran, T. P. (1996). Questions, Options, and Criteria: Elements of Design Space. In Moran, T. P., Carroll, J. M. (Eds.). *Design Rationale: Concepts, Techniques, and Use Computers, Cognition, and Work,* 53-105. Mahwah, New Jersey: Lawrence Erlbaum Associates.

180. Mayhew, D. J. (1992). *Principles and Guidelines in Software User Interface Design*. Englewood Cliffs, N.J. : Prentice Hall.

181. McCormick, M. S. (1996). *How to Get There From Here: Wayfinding in Complex Environments.* (Ph. D. Dissertation, Texas A&M University.)

182. McDonald, T. P., Pellegrino, J. W. (1993). Psychological Perspectives *on* Spatial Cognition. In Gorling, T. & Golledge, R. G. (Eds.) *Behavior and Environment: Psychological and Geographical Approaches.* Amsterdam: North-Holland. 170-192.

183. Microsoft Corp. (2001). *Streets & Trips*.

184. Miller, G. A., Galanter, E., Pribram, K. (1960). *Plans and the Structure of Behavior*. New York: Holt.

185. Miller, G. A., Johnson-Laird, P. N. (1976). *Language and Perception*. London: Cambridge University Press.

186. Mine, M. R., Brooks, F. P., Jr., Sequin, C. H. (1997). Moving Objects in Space: Exploiting Proprioception in Virtual-Environment Interaction. *Computer Graphics Proceedings, SIGGRAPH 97*. New York, NY, USA: ACM, 19-26.

187. Moeser, S. D. (1988). Cognitive Mapping in a Complex Building. *Environment and Behavior*, 20, 21-49.

188. Monk, A. F. (1990). Getting to Known Locations in a Hypertext. In R. McAleese, C. Green (Eds.). *Hypertext: State of the Art*, London: Intellect, 20-27.

189. Moran, T. P., Carroll, J. M. (Eds.) (1996). *Design Rationale: Concepts, Techniques and Use*. Mahwah, NJ: Lawrence Erlbaum Associates.

190. Nardi, B. Anderson, K., Erickson, T. (1995). Filing and Finding Computer Files. *East-West International Conference on Human-Computer Interaction: Proceedings of the EWHCI'95*, 162-179. Intl. Centre for Scientific & Technical Information.

191. National Geographic Society. (1997). *National Geographic Photo Gallery*. CD-ROM.

192. Newby, G. B. (1992). An Investigation of the Role of Navigation for Information Retrieval. *Proceedings of the ASIS Annual Meeting*, v 29 1992. Medford, NJ: Learned Information Ltd. 20-25.

193. Newell, A., Simon, H. A. (1972). *Human Problem Solving.* Englewood Cliffs, N. J.: Prentice-Hall.

194. Nickerson, R. S. (1981). Understanding Signs: Some Examples of Knowledge Dependent Language Processing. *Information Design Journal*, 2 (2).

195. Nielsen, J. (1990). The Art of Navigating Through Hypertext. *Comm*. *ACM* 33, 3 (Mar.), 296-310.

196. Nielsen, J. Mack, R. L. (Eds.) (1994). *Usability Inspection Methods.* New York, NY: John Wiley & Sons, Inc.

197. Norman, D. A. (1986). Cognitive Engineering. In Norman, D. A., Draper, S. W. *User Centered System Design: New Perspectives on Human-Computer Interaction.* Hillsdale, NJ: Lawrence Erlbaum Associates.

198. Norman, D. A. (1988). *The Psychology of Everyday Things.* New York: Basic Books. Republished (1990) as *The Design of Everyday Things.* New York: Doubleday.

199. Norman, D. A., Draper, S. W. (1986). *User Centered System Design: New Perspectives on Human-Computer Interaction.* Hillsdale, NJ: Lawrence Erlbaum Associates.

200. Norman, K. L., Chin, J. P. (1988). The Effect of Tree Structure on Search in a Hierarchical Menu Selection System. *Behaviour and Information Technology,* v.7 n.1. 51-65.

201. Oatley, K. G. (1977). Inference, Navigation, and Cognitive Maps. In Johnson-Laird, P. N., Wason, P. C. (Eds.). *Thinking: Readings in Cognitive Science*, Cambridge: Cambridge University Press, 537-547.

202. O'Neill, M. (1991). A Biologically Based Model of Spatial Cognition and Wayfinding. *Journal of Environmental Psychology*. Vol 11(4) Dec, 299-320.

203. O'Neill, M. J. (1991). Effects of Signage and Floor Plan Configuration on Wayfinding Accuracy. *Environment and Behavior*. Vol. 23, No. 5 (Sept.). 553-574.

204. O'Neill, M. J. (1991). Evaluation of a Conceptual Model of Architectural Legibility. *Environment and Behavior*, 23, 259-284.

205. O'Neill, M. J. (1992). Effects of Familiarity and Plan Complexity on Wayfinding in Simulated Buildings. *Journal of Environmental Psychology*, 12. 319-327.

206. O'Neill, M. J. (1992). Neural Network Simulation as a Computer-Aided Design Tool for Predicting Wayfinding Performance. In Kalay, Y. E. (Ed.) *Evaluating and Predicting Design Performance*. New York, NY: Wiley and Sons.

207. Orasanu, J., Connolly, T. (1993). The Reinvention of Decision Making. In Klein, G. A., Orasanu, J., Calderwood, R. Zsambok, C. E. (Eds.) *Decision Making in Action: Models and Methods*. Norwood, NJ: Ablex. 3-20.

208. Page, M. (1990). *Active Learning: Historical and Contemporary Perspectives*. MA: University of Massachusetts. (ERIC Document Reproduction Service No. ED 338 389).

209. Pang, G., Takahashi, K., Yokota, T., Takenaga, H. (1995). Drivers Route Selection: A Philosophical Consideration and User-Interface. *Vehicle Navigation and Information Systems Conference (VNIS) 1995*. Piscataway, NJ, USA: IEEE, 95CH35776, 147-154.

210. Passini, R. (1980). Wayfinding in Complex Buildings: An Environmental Analysis. *Man-Environment Systems*, 10, 31-40.

211. Passini, R. (1980). Wayfinding: A Conceptual Framework. *Man-Environment Systems*, 10, *22-30.*

212. Passini, R. (1984). Spatial Representation: A Wayfinding Perspective. *Journal of Environmental Psychology*, 4, 153-164.

213. Passini, R. (1992). *Wayfinding in Architecture*. 2nd Edition. New York: Van Nostrand Reinhold.

214. Passini, R. (1996). Wayfinding Design: Logic, Application and Some Thoughts on Universality. *Design Studies*, Vol 17. Great Britain: Elsevier Science Ltd, 319-331.

215. Passini, R., Proulx, G. (1988). Wayfinding without Vision: An Experiment with Congenitally Totally Blind People. *Environment and Behavior*, Vol. 20, No. 2, March. 227-252.

216. Pausch, R., Burnette, T., Brockway, D., Weiblen, M. E. (1995). Navigation and Locomotion in Virtual Worlds via Flight into Hand-Held Miniatures. *ACM SIGGRAPH `95 Conference Proceedings, Computer Graphics*, July 1995.

217. Peponis, J., Zimring, C. M., Choi, Y. K. (1990). Finding the Building in Wayfinding. *Environment and Behavior*, 22 (5). 555-590.

218. Perlin, K., Fox, D. (1993). An Alternative Approach to the Computer Interface. *Proceedings of the ACM SIGGRAPH 93 Conference*, New York, NY: ACM Press, 57-64.

219. Peterson, B., Wells, M., Furness III, T. A., Hunt, E. (1998). The Effects of the Interface on Navigation in Virtual Environments. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting.* Santa Monica, CA: Human Factors and Ergonomics Society, 1496-1500.

220. Peterson, M. A., Nadel, L., Bloom, P., Garrett, M. F. (1996). Space and Language. In Bloom, P., Peterson M. A., Nadel, L., Garrett, M. F. (Eds). *Language and Space.* Cambridge, MA: MIT Press.

221. Prabhu, G. V. (1995). *In-Vehicle Navigation Displays: A Human Attention and Information Processing Model.* PhD Dissertation. Department of Industrial Engineering. State University of New York at Buffalo.

222. Presson, C. C., Montello, D. R. (1988). Points of Reference in Spatial Cognition: Stalking the Elusive Landmark. Conference on Landmarks in Spatial Cognition and Spatial Development (1988, Tempe, Arizona). *British Journal of Developmental Psychology*, Nov Vol 6(4), 378-381.

223. Prieto-Dìaz, R. (1990). Domain Analysis: An Introduction. *SIGSOFT Software Engineering Notes*. Vol.15, no.2 (April). 47-54.

224. Purcell, A. T. Gero, J. S. (1996). Design and Other Types of Fixation. *Design Studies*, Vol. 17. 363-383.

225. Rada, R., Murphy, C. (1992). Searching versus Browsing in Hypertext. *Hypermedia*, 4, 11-30.

226. Rand, G. Pre-Copernican Views of the City. *Architectural Forum*, 131, 2 (Sep.). 76-81. 1969.

227. Reitman, W. R. (1964). Heuristic Decision Procedures, Open Constraints, and the Structure of Ill-Defined Problems. In Shelly, M. W., II, Bryan, G. L. (Eds.) *Human Judgments and Optimality*. New York: Wiley.

228. Rittel, H. W. J., Webber, M. M. (1973). Dilemmas in a General Theory of Planning. *Policy Sciences*, 4, 155-169.

229. Robertson, G., Czerwinski, M., van Dantzich, M. (1997). Immersion in Desktop Virtual Reality. Proceedin*gs of the ACM Symposium on User Interface Software and Technology*, 11-19.

230. Ruddle, R. A., Payne, S. J., Jones, D. M. (1999). The Effects of Maps on Navigation and Search Strategies in Very-Large-Scale Virtual Environments. *Journal of Experimental Psychology: Applied*, Vol 5(1), 54-75.

231. Russell, D. M., Stefik, M. J., Pirolli, P., Card, S. K. (1993). Cost Structure of Sensemaking. *Conference Proceedings on Human Factors in Computing Systems 1993*. New York, NY: ACM, 269-276.

232. Sadalla, E. K., Burroughs, W. J., Staplin, L. J. (1980). Reference Points in Spatial Cognition. *Journal of Experimental Psychology*, 6, 516-528.

233. Sadalla, E. K., Staplin, L. J. (1980). The Perception of Traversed Distance: Intersections. *Environment and Behavior*, 12, 167-182.

234. Schaffer, D., Zuo, Z., Bartram, L., Dill, J., Dubs, S., Greenberg, S., Roseman, M. (1993). Comparing Fisheye and Full-Zoom Techniques for Navigation of Hierarchically Clustered Networks. *Proceedings of the Graphics Interface 1993*. Publ. by Canadian Information Processing Society, Toronto, Ontario, Canada, 87-96.

235. Schön, D. A. (1983). *The Reflective Practitioner: How Professionals Think in Action.* Basic Books, Inc.

236. Schön, D. A. (1987). *Educating the Reflective Practitioner.* San Francisco, CA: Jossey-Bass Publishers.

237. Schooler, J. W., Fallshore, M., Fiore, S. (1995). Epilogue: Putting Insight into Perspective. In Sternberg, R. J., Davidson, J. E. (Eds.) *The Nature of Insight.* Cambridge, MA: MIT Press. 559-587.

238. Schraagen, J. M., Chipman, S. F., Shalin, V. L. (2000). *Cognitive Task Analysis*. Mahwah, NJ: Lawrence Erlbaum Associates.

239. Seuss, Dr. (1955). *ON BEYOND ZEBRA!* New York: Random House.

240. Seuss, Dr. (1965). *I Had TROUBLE in Getting to SOLLA SOLLEW*. New York: Random House.

241. Seuss, Dr. (1975). *Oh, the Thinks You Can Think!* New York: Random House (Beginner Books).

242. Seuss, Dr. (1990). *Oh, the Places You'll Go!* New York: Random House.

243. Shapiro, A. M. (1998). Promoting Active Learning: The Role of System Structure in Learning from Hypertext. *Human-Computer Interaction*; Vol 13(1), 1-35.

244. Shneiderman, B. (1983). Direct Manipulation: A Step Beyond programming Languages. *IEEE Computer*, August. 57-69.

245. Siegel, A. W., White, S. H. (1975). The Development of Spatial Representations of Large-Scale Environments. In Reese, H. W. (Ed.). *Advances in Child Development and Behavior.* New York: Academic Press.

246. Simon, H. A. (1957). *Models of Man*. New York: Wiley.

247. Simon, H. A. (1971). Style in Design. *Proceedings of the 2nd Annual Conference of the Environmental Design Research Association*. Pittsburgh PA: Carnegie Mellon University, 1 - 10.

248. Simon, H. A. (1973). The Structure of Ill-Structured Problems. *Artificial Intelligence,* 4, 181-201.

249. Simon, H. A. (1978). Information-Processing Theory of Human Problem Solving. Estes, W. K. (Ed.) *Handbook of Learning and Cognitive Processes: V. Human Information Processing.* Hillsdale, NJ: Lawrence Erlbaum.

250. Simon, H. (1986). Decision Making and Problem Solving. *Research Briefings 1986: Report of the Research Briefing Panel on Decision Making and Problem Solving.* National Academy of Sciences. National Academy Press, Washington, DC. http://www.dieoff.org/page163.htm

251. Simon, H. A. (1972). *The Sciences of the Artificial.* Cambridge, MA: MIT Press.

252. Simon, H. A. (1996). *The Sciences of the Artificial.* 3^{rd} Edition. Cambridge, MA: MIT Press.

253. Simpson, A., McKnight, C. (1990). Navigation in Hypertext: Structural Cues and Maps. In R. McAleese, C. Green (Eds.). *Hypertext: State of the Art.* London: Intellect, 73-83.

254. Smith, D. C., Irby, C. H., Kimball, R. B., Harslem, E. F. (1982). The Star User Interface: An Overview. *Proceedings of the AFIPS National Computer Conference,* 515-528.

255. Song, D., Norman, M. (1993). Nonlinear Interactive Motion Control Techniques for Virtual Space Navigation. *1993 IEEE Annual Virtual Reality International Symposium.* IEEE 93CH3336-5, IEEE Service Center, Piscataway, NJ, USA, 111-117.

256. Spence, R. (1999). A Framework for Navigation. *International Journal of Human-Computer Studies*; Vol 51(5) Nov, 919-945.

257. Spence, R., Apperley, M. (1982). Data Base Navigation: An Office Environment for the Professional. *Behaviour & Information Technology,* 1 (1), 43-54.

258. Stern, E., Portugali, J. (1999). Environmental Cognition and Decision Making in Urban Navigation. In Golledge, R. G. (Ed.) *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes.* Baltimore: The Johns Hopkins University Press, 99-119.

259. Stevens, A., Coupe, P. (1978). Distortions in Judged Spatial Relations. *Cognitive Psychology*, (10), 422-437.

260. Streeter, L. A., Vitello, D. (1986). A Profile of Drivers' Map-Reading Abilities. *Human Factors* Vol. 28(2, Apr.), 223-239.

261. Streeter, L. A., Vitello, D., Wonsiewicz, S. W. (1985). How to Tell People Where to Go: Comparing Navigational Aids. *International Journal of Man-Machine Studies*, vol. 22.

262. Strong, G. W., Strong, K. O. (1991). Visual Guidance for Information Navigation: A Computer-Human Interface Design Principle Derived from Cognitive Neuroscience. *Interacting with Computers*, (Aug.) vol. 3(2), 217-231.

263. Tan, D. S., Robertson G. G., Czerwinski, M. (2001). Exploring 3D Navigation: Combining Speed-Coupled Flying with Orbiting. *Proceedings of ACM CHI 2001 Conference on Human Factors in Computing Systems*, 418-425.

264. Templeman, J. N., Denbrook, P. S., Sibert, L. E. (1999). Virtual Locomotion: Walking in Place through Virtual Environments. *Presence*, Vol. 8, No. 6, 598-617.

265. Teske, J. A., Balser, D. P. (1986). Levels of Organization in Urban Navigation. *Journal of Environmental Psychology*, (Dec.) vol. 6(4), 305-327.

266. Thirslund, S. (1999). *Vikingetidens Navigation og Amerikas Opdagelse*. Skjern, Denmark: Gullanders Bogtrykkeri.

267. Thorndyke, P. W., Hayes-Roth, B. (1982). Differences in Spatial Knowledge Acquired from Maps and Navigation. *Cognitive Psychology*, (Oct.) vol. 14(4), 560-589.

268. Timmermans, H. (1991). Decision-making Processes, Choice Behavior, and Environmental Design: Conceptual Issues and Problems of Application. In Gärling, T., Evans, G. (Eds.) *Environment, Cognition, and Action: An Integrated Approach.* New York, NY, USA: Oxford University Press. 63-77.

269. Tognazzini, B. (1992). *TOG on Interface.* Reading, MA: Addison-Wesley Publishing Company.

270. Tolman, E. C. (1948). Cognitive Maps in Rats and Men. *Psychological Review*, 55, 189-208. Reprinted in Downs, R. M., Stea, D. (Eds.) (1973). *Image and Environment; Cognitive Mapping and Spatial Behavior*.

271. Tromp, J. G., Dieberger, A. (1995). MUDs as Text-Based Spatial User Interfaces And Research Tools. *Journal of Intelligent Systems*; vol. 5 no 2-4, 179-202.

272. Ullman, D. G., Dietterich, T. G., Stauffer, L. A. (1988). A Model of the Mechanical Design Process Based on Empirical Data. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AI EDAM*, 2. 33-52.

273. Varma, J. R. (1992). Computer Graphics, Peripheral Vision and Non-Euclidian Geometry. *Computer Graphics*, v. 16 n. 3 (Fall), 253-258.

274. Van Hoe, R., Poupeye, K., Vandierendonck, A., De Soete, G. (1990). Some Effects of Menu Characteristics and User Personality on Performance with Menu-Driven Interfaces Individual Differences in User Behaviour. *Behaviour and Information Technology,* v.9 n.1. 17-29.

275. Vinson, N. G. (1999). Design Guidelines for Landmarks to Support Navigation in Virtual Environments. CHI *99 Conference Proceedings.* New York, NY: ACM Press. 278-285.

276. Wallace, D. F., Anderson, N. S., Shneiderman, B. (1987). Time Stress Effects on Two Menu Selection Systems Menu Design and Use. *Proceedings of the Human Factors Society 31st Annual Meeting*.727-731.

277. Watts, J. (1994). Navigation in the Computer Medium: A Cognitive Analysis. *Proceedings of the Human Factors and Ergonomics Society 1994,* Human Factors and Ergonomics Society, Inc., Santa Monica, CA, USA, 310-314.

278. Weisman, G. D. (1981). Evaluating Architectural Legibility: Wayfinding in the Built Environment. *Environment and Behavior*, 13, 189-204.

279. Wexelblat, A., Maes, P. (1999). Footprints: History-Rich Tools for Information Foraging. *CHI 99 Conference Proceedings.* New York, NY: ACM Press. 270-277.

280. Wickens, C. D. (1992). *Engineering Psychology and Human Performance*. 2nd Ed. London: Harper Collins.

281. Wickens, C. D., Hollands, J. G. (2000). Navigation and Interaction in Real and Virtual Environments. Ch. 5. *Engineering Psychology and Human Performance.* 3rd Ed. Upper Saddle River, N.J. : Prentice Hall.

282. Williamson, A. (1998). Moneypenny: Lessons from the Messy Desk. *Interacting with Computers*, v.9 n.3, 241-267.

283. Wiltschko, R., Wiltschko, W. (1999). Compass Orientation as a Basic Element in Avian Orientation and Navigation. In Golledge, R. G. (1999). *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes.* Johns Hopkins University Press, 259-293.

284. Woods, D. D. (1984). Visual Momentum: A Concept to Improve the Cognitive Coupling of Person and Computer. *International Journal of Man-Machine Studies*, 21, 229-244.

285. Wright, P., Hull, A. J., Lickorish, A. (1993). Navigating in a Hospital Outpatients' Department: The Merits of Maps and Wall Signs. *Journal of Architectural & Planning Research*. (Spr.) vol. 10(1), 76-89.

286. Wright, P., Lickorish, A. (1990). An Empirical Comparison of Two Navigation Systems for Hypertexts. In R. McAleese, C. Green (Eds.). *Hypertext: State of the Art*, 84-93, London: Intellect.

287. Wright, P., Lickorish, A. (1994). Menus and Memory Load: Navigation Strategies in Interactive Search Tasks. *International Journal of Human Computer Studies*, vol. 40 no. 6 (June), 965-1008.

288. Zimring, C., Gross, M. (1991). Searching for the Environment in Environmental Cognition Research. In Gärling, T., Evans, G. (Eds.) *Environment, Cognition, and Action: An Integrated Approach.* New York, NY, USA: Oxford University Press, 78-95.

289. Zsambok, C. E., Klein, G. (1997). *Naturalistic Decision Making*. Mahwah, N.J.: Lawrence Erlbaum Associates.