Locomotional Structure in Service of Wayfinding:
A Partial Design Theory

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ABSTRACT

This paper introduces a partial theory of design for locomotion. The goal of the theory is to help generate actual designs by informing design content. Assuming that locomotion is always in service of the cognitive task of wayfinding, the theory relates cognitive constructs of wayfinding problem-solving and decision-making to features of locomotional design. Specifically, the theory suggests that the complexity of wayfinding reasoning is controlled, in part, by how closely the set of locations and ways of moving between them provided in the environment matches those necessitated by the user's task.

The theory has been applied to the design of support for the task of moving between individual objects in a multiscale environment. The resulting *lodestones and leylines* design constrains locomotion based on inter-object geometry and uses an approximate indication of direction from the user to predict a target location and guide movement. Preliminary results of a pilot study indicate that this technique dramatically improves wayfinding performance over locomotional techniques based on geometry of the space itself.

KEYWORDS

Generative Design Theory, Principled Design, Navigation, Wayfinding, Locomotion, Problem-Solving, Decision-Making, Multiscale, Zooming User Interface, Jazz.

INTRODUCTION

Take a moment to examine the two maps shown above, picturing yourself having to get from **o** to **x**. Which environment do you think would require more of your attention and concentration? If you drove it every few months? Every few weeks? Every day?

Presumably, your response was along the lines of "Uhm, the left one?" Now ask yourself "Why would the left one re-

quire more cognitive resources?"

Wayfinding—the task of determining how to get to where one wants to go and directing the activities needed to get there—is fundamental to most human activity, including interacting with computers [11]. *Locomotion*—the task of moving and controlling movement—is inherently complementary to wayfinding [11]. Wayfinding is the process of reasoning, locomotion is what is reasoned about.

If you have not already done so, verify for yourself that the routes from **o** to **x** in the two maps are identical. That is, the required locomotion—the actual movement—is the same. However, the locomotional options—the structure offered in the environment—differ. There are many more options in the structure on the left, making wayfinding much more complex. *Locomotional design* determines what movement is possible in the environment; *wayfinding design* provides information about possible movement. Locomotional structure is one aspect of locomotional design that influences the difficulty of wayfinding [19, 20, 21].

In spite of the interdependency of wayfinding and locomotion, locomotional and wayfinding design are usually divorced in the design of most electronic worlds. Typically, a generic locomotional design is developed and provided as part of an application framework or other general-purpose tool, e.g., the familiar mouse and pixel locomotion of graphical user interfaces, or the node and hyperlink movement of hypermedia. Such a generic locomotional design is then adopted with little or no modification when wayfinding support is designed, usually when an information structure or application is developed. Consequently, users as well as wayfinding designers are often forced to solve wayfinding problems that could have been eliminated by the locomotional design.

This paper introduces a generative theory of the relationship between wayfinding and locomotion, and of the implications of this relationship for locomotional design. It is a theory of *design* based on cognitive considerations as opposed to a theory of *cognition*. That is, the theory uses cognitive evidence to relate cognitive constructs of wayfinding to elements of locomotional design rather than explaining the effect of locomotion on navigational reasoning. The emphasis is on design of and wayfinding in large-scale environments—in which there is no single point from which the environment can be perceived in its entirety—rather than on small-scale environments or local views of large-scale environments.

The partial theory introduced concerns the static aspects of locomotion; in particular, the design of *locomotional structure*—the network of locations and routes along which movement is possible. It is based on a model of wayfinding as a human problem-solving and decision-making activity. Application and utility of the theory is demonstrated by way of an exercise whose goal is to design locomotional support that reduces the cognitive overhead of wayfinding in a multiscale spatial environment (Jazz [3, 10]). Preliminary analysis of data from a pilot study of this design shows promising results.

RELATED WORK

The idea of shaping locomotional design to accommodate wayfinding needs is not itself novel or even particularly radical. There have been efforts to understand how to do so in the physical world. Most of these are aimed at evaluating the wayfinding difficulties of real or proposed locomotional structures [14, 19], although there have been some efforts toward developing generative theory [16]. The work, in both cases, is typically based on first-hand observations of behavior and takes the environmental constraints of the physical world for granted. The present work, in contrast, seeks to understand how to fashion environmental constraints to control wayfinding difficulty.

In electronic spaces, work on informing locomotional design has mostly focused on the mechanics of input devices such as mice, trackballs and joysticks [1]. These efforts often take perceptual considerations such as eye-hand coordination into account [8], but rarely touch on cognitive considerations. Conversely, work on wayfinding design usually focuses on using general cognitive considerations to provide guiding information, such as signage, landmarks, etc. [23]. The possibility of changing locomotional design to alter fundamental wayfinding problems is usually not considered. There seem to be no prior efforts to provide a generative theory of locomotional design in service of wayfinding in electronic spaces.

Even so, there are many cases of individual designs that—more or less intentionally—use locomotional design to simplify wayfinding. *Constraining designs* restrict where the user can go in the environment but do not alter the environment itself. Examples of constraining designs include revealing links selectively as a student learns in a hypertext structure [4], and restricting movement to remain within a certain region relative to objects in a virtual environment [7]. *Restructuring designs* alter the environment to provide new means of access to certain places. For example, query relevance metrics, history mechanisms and bookmarks provide special access to places deemed particularly interesting. Of course, it is possible for a design to be both constraining and restructuring, as well as employing other means to support wayfinding. Note that both approaches follow from the proposed theory (and, indeed, the categorization was suggested by it). As shall be seen, the design exercise yields a constraining design.

A PARTIAL THEORY OF LOCOMOTIONAL DESIGN

The theory is based on the common (although often unstated) assumption that wayfinding can be modeled as a problem-solving and decision-making activity [13, 14, 21]. Problem-solving and decision-making (and, hence, wayfinding) entail determining a sequence of actions that will lead to a desired goal, including discovering what options are available for each action and deciding among them [13, 22]. It is here assumed that wayfinding problem-solving and decision-making is performed in the service of some *superordinate task*—the task the user is trying to accomplish.

The actions that wayfinding problem-solving and decision-making seeks to determine are sequences of movement or locomotional steps through an environment. The desired goal is a location or sequence of locations in the environment, the *target location* or *destination*. It may be distinguished by objects residing—possibly temporarily—at that location ("Gramma's house") or by other properties of the location ("a good sunset view," "Route 66").

The options of wayfinding problem-solving and decision-making are different actions (sequences of locomotional steps) believed to lead from the present location to the target destination or, at least, the next steps believed to lead to the destination. Sequences of steps are typically characterized by the set of intermediate locations through which they pass, and are often described in terms of those intermediate locations. For the present purposes, a *route* is an ordered set of locations.

A set of locations and routes between them is called a *structure of locomotion* (or *locomotional structure*). A *cognitive locomotional structure* is a set of locations and routes *in the mind* of the wayfinding problem solver. It is the set of locations and routes that the wayfinder thinks about in the course of wayfinding reasoning. If the wayfinding task is to succeed, the cognitive locomotional structure must reflect some *mechanical locomotional structure*—a locomotional structure *actually offered* in the environment. This mechanical locomotional structure part of the locomotional design and results from a combination of mechanism and structure of movement—cars and roads, trains and tracks.

In the physical world, design of the mechanical locomotional structure is overwhelmingly constrained by the laws of natural physics. In electronic spaces, the locomotional designer controls the laws of physics of the space. That is, the designer controls what constitutes a location and how it can be reached. In electronic spaces, the main source of constraints is the superordinate task. This defines the *task-defined locomotional structure*: the structure of locations and routes critical to its completion.

Figure 1 illustrates the distinctions between the three types of locomotional structure. Figure 1:1 shows the task-defined locomotional structure for the hypothetical task of "having to get from o to x" introduced earlier—the two locations and as direct a route as possible between them.

2-4 Possible mechanical locomotional structures enabling completion of task

1 Task-defined locomotional structure

1c-4c Cognitive locomotional structures corresponding to locomotional structures in 1-4. Circled black lines indicate parts of mechanical locomotional structure that *must* figure in wayfinding reasoning, gray lines parts that do not.
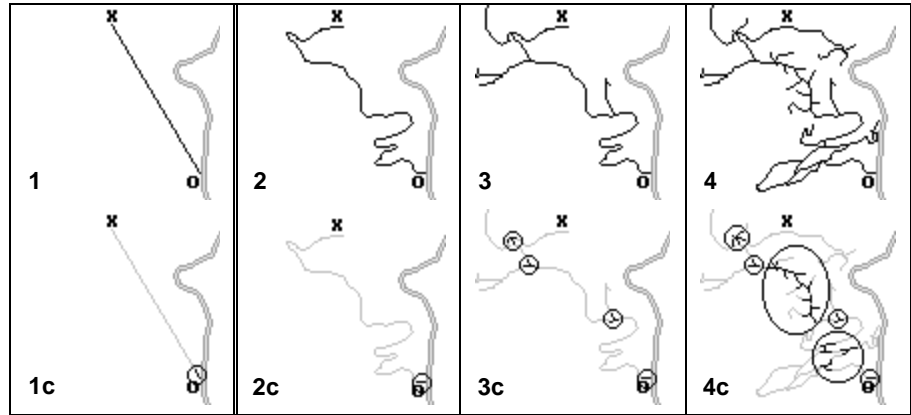
Figure 1 Locomotional structures related to task of "having to get from **o** to **x**"

Figure 1:1c shows the cognitive locomotional structure corresponding to this task-defined locomotional structure. Figure 1:2-4 show possible mechanical locomotional structures that enable completion of the task in some physical environment. The structure in Figure 1:3 might result from an inability to predict the exact destination, but only to predict that x is at one of a small set of locations. The structure in Figure 1:4 might result either from a total inability to predict the destination, or from a design goal of increasing wayfinding complexity. Figure 1:2c-4c show the cognitive locomotional structures corresponding to these suggested mechanical locomotional structures.

Often, in the design of electronic spaces, the intent is to increase usability, including reducing the cognitive overhead of wayfinding as much as possible. This is achieved by matching the mechanical locomotional structure to the task-defined locomotional structure as closely as possible. However, in some cases, a design goal is to make wayfinding more challenging, for instance, in some game designs. This can be achieved by making the mechanical locomotional structure a more complex version of the task-defined locomotional structure. Note that it is always necessary for the mechanical structure to form a superset of the task-defined structure, or the wayfinding task is impossible: You literally "can't get there from here." Thus, the designer's task is to identify the task-defined locomotional structure as well as possible, and match the mechanical locomotional structure as closely to it as desired and possible within other design constraints.

Figure 1 also illustrates that wayfinding reasoning is needed at *branch* (or *branching*) *points*—locations in the environment where the locomotional options change. This accounts for the intuition that following the route in the map on the left in the introduction would require more cognitive resources than that on the right: the corresponding required cognitive locomotional structures are represented in Figure 1:4c and Figure 1:3c, respectively.

General problem-solving and decision-making theory shows that the number and complexity of decisions significantly affect problem-solving and decision-making performance [17]. In wayfinding, the number and complexity of decisions is a function of the number of branch points and the number of options considered at each branch point. These are determined by the number of destinations and the number of distinct routes in the mechanical locomotional structure, respectively.

In other words, if the goal of the design is to increase wayfinding performance, the designer should aim to limit the number of destinations and the number of distinct routes in the mechanical locomotional structure. Of course, other design goals may make it necessary, or even desirable, to increase the complexity of wayfinding problem-solving and decision-making. In such cases, it may be desirable not to minimize either number of branch points or number of distinct routes.

Using knowledge of the specifics of their design situation, the designer, will likely need to trade off between the number of branch points and the number of options at each. The nature of this tradeoff in wayfinding requires further exploration, but there is evidence from research on menus that the distribution of branch points and options is depends, to a significant extent, on characteristics of the superordinate task and the user's knowledge [18].

In summary, an important part of the locomotional designer's task is the design of the mechanical locomotional structure—the set of locations and ways of moving between them actually available in the environment. This locomotional structure must reflect the task-defined locomotional structure—the set of locations and ways of moving between them necessitated by the superordinate task. The closer this match is, the easier it is for the user to entertain a useful cognitive locomotional structure—the set of locations and ways of moving between them that take part in wayfinding reasoning. The complexity of the mechanical locomotional structure is a function of the number of branch points and the number of options at each. The fewer branch points and the fewer options at each, the simpler the necessary cogni-

tive locomotional structure, implying less cognitive over-head required for wayfinding.

A DESIGN EXERCISE

The following design exercise is presented to illustrate both the application and the utility of the theory. The goal of the exercise is to provide basic locomotional utilities in a multi-scale environment. The design is intended for a single-user system, and it is assumed that the user is working in their own system. That is, the user is familiar with the spatial layout and this layout may not be altered by the system. Allowing the user to get to where they want to go, quickly, is a design goal, but spatial learning is not, so wayfinding should be as simple as possible.

The exercise focuses on the task of interacting with existing objects, leaving the demands of creation and placement of new objects for later consideration. This distinction be-tween browsing and editing is common in information tools, for example, web browsers vs. page editors or image view-ers vs. image editors, but is often not acknowledged in basic locomotional design. However, there is evidence that many individuals spend more time interacting with existing ob-jects than in creating new ones. Thus, it seems worthwhile to explore the two types of tasks individually before assum-ing that a unified locomotional design is always necessary or even appropriate.

Traditional Mechanical Locomotional Structure

Jazz [3, 10] is an application framework for designing and building multiscale electronic worlds and is the computa-tional environment for this design. Like its predecessor, Pad++ [2], Jazz employs an interaction metaphor of a con-ceptually infinite two-dimensional surface that can be viewed at an infinite range of magnifications. Objects have position and extent on the surface, and can alter their visi-bility depending on the magnification (scale) of the view.

Locomotion in Jazz is by panning (moving across the sur-face) and zooming (changing the scale of the view). Tradi-tionally, the center of the zoom is a point on the surface around which the view is expanded or contracted. Move-ment—either by panning or zooming—leads to other views of the surface, generally defined by the point at the center of the viewing window combined with the scale of the view, defined in terms of *space-scale* coordinates (surface space x view magnification) [5]. Any point in space-scale can be a destination, and routes are space-scale trajectories leading from any point to any other point.

With this model, getting lost—not knowing where to go next to get to one's goal—is a common problem [12]. Be-ing lost or disoriented is often caused by "desert fog" [12], an insidious condition wherein the current view of the envi-ronment provides no clues upon which to base wayfinding decisions, for instance, a blank screen. Conventional pan and zoom offers no sure escape from desert fog, making disorientation inevitable and systematic movement nearly impossible.

UNDERSTANDING SPACE-SCALE DIAGRAMS*
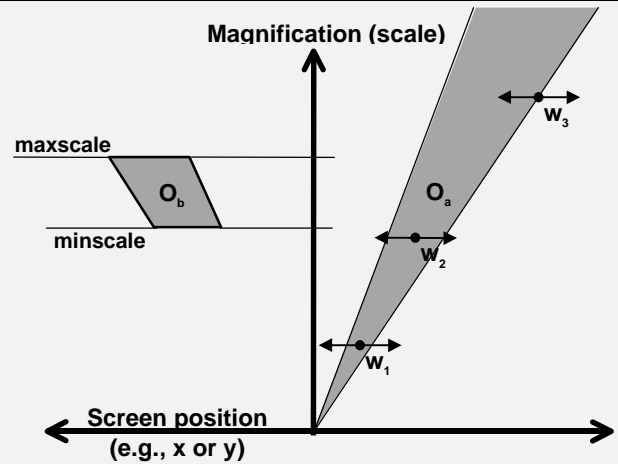
Space-scale diagrams were developed as a tool for under-standing multiscale spaces [5]. They show the apparent change in size and position of an object relative to the magnification of the view. In the sample diagram above, the horizontal axis indicates location in screen-space (e.g., x-coordinate) and the vertical axis indicates degree of magni-fication (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 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 mag-nified. In practice, an object typically has a minimum magni-fication at which it is rendered, its *minscale*, or automati-cally disappears when it is smaller than one pixel. Objects also have a maximum effective magnification, the *max-scale*; e.g., when they fill the view uniformly they are often culled by the rendering system. These limits are shown schematically for object O_b in the sample diagram.
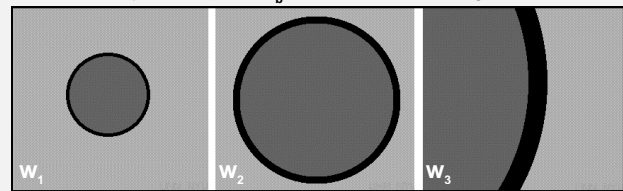
A particular view of the world is defined by the position in space and scale of a window with a given width. This is represented in a space-scale diagram by a horizontal line whose midpoint represents of the center of the window. (Note that we assume uniform magnification across any particular view.) Since the width of the window is unaffected by the magnification of the view, a line representing a par-ticular window will have the same width throughout the dia-gram. In the sample diagram, w_1 is a view in which O_a fills the middle third of the window, as shown in the first of the screen-shots above. w_2 has zoomed in on (the now magni-fied) O_a, as shown in the second screen-shot. w_3 has zoomed in further and panned right almost half a window width, as shown in the third screen-shot.

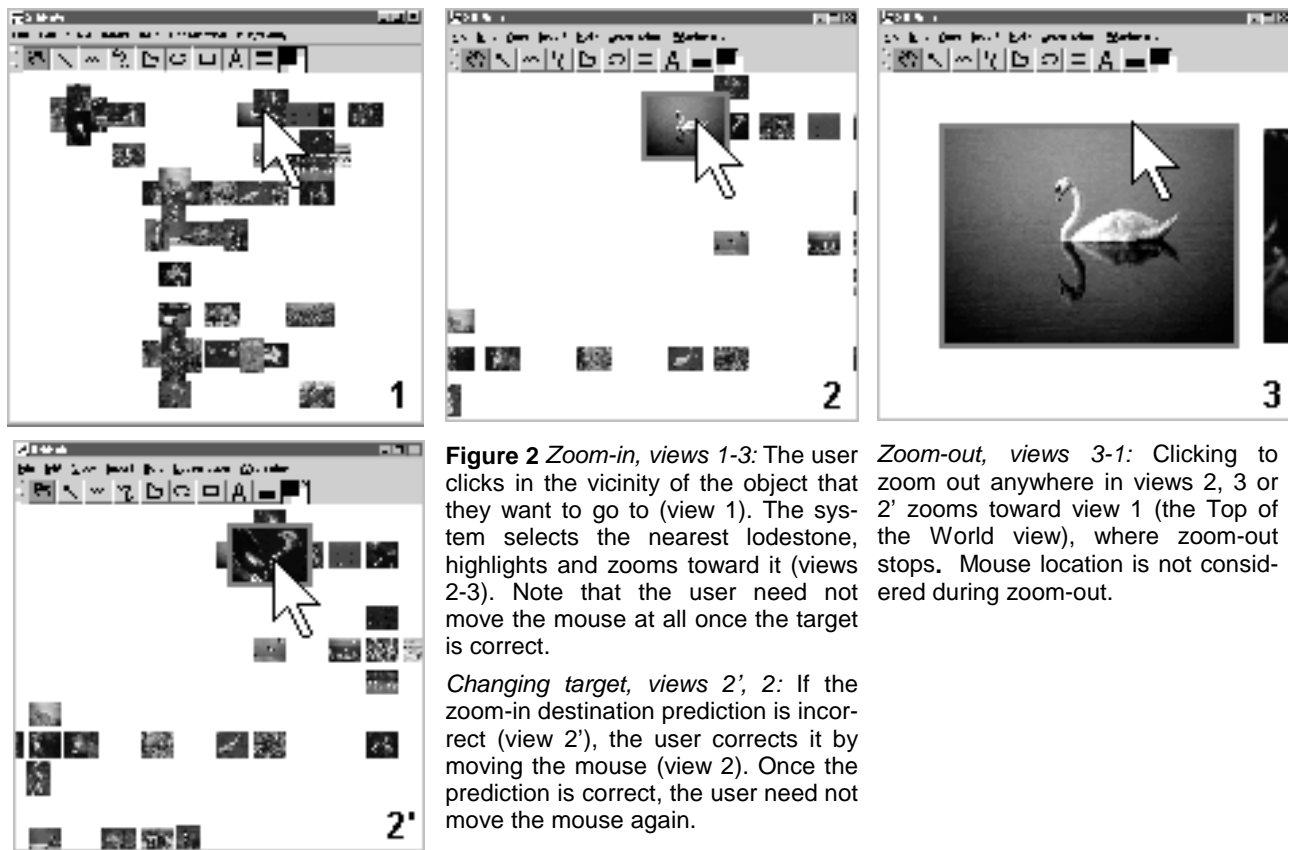* Reprinted from Jul and Furnas [12] © 1998 ACM.

Figure 2 *Zoom-in, views 1-3:* The user clicks in the vicinity of the object that they want to go to (view 1). The system selects the nearest lodestone, highlights and zooms toward it (views 2-3). Note that the user need not move the mouse at all once the target is correct.

Changing target, views 2', 2: If the zoom-in destination prediction is incorrect (view 2'), the user corrects it by moving the mouse (view 2). Once the prediction is correct, the user need not move the mouse again.

Zoom-out, views 3-1: Clicking to zoom out anywhere in views 2, 3 or 2' zooms toward view 1 (the Top of the World view), where zoom-out stops. Mouse location is not considered during zoom-out.

Task-Defined Locomotional Structure

It is assumed, for the present purposes, that the superordinate task requires interaction with individual objects. Thus, the task-defined locomotional structure is entirely defined by the geometry of the layout of objects. Locations are single objects (or, rather, views of the surface in which an object can be seen at a reasonable scale) and routes are direct links from anywhere to single objects.

The mechanical locomotional structure offered by the traditional model of locomotion is, in contrast, defined by the geometry of the space itself. This discrepancy is the source of the difficulties posed by desert fog. The user wants to get to some object, but only knows approximately where it is. When they encounter desert fog, few of the destinations offered by the mechanical locomotional structure—points in space-scale—correspond to destinations in the task-defined locomotional structure—surface views that contain objects. In fact, at any location in the mechanical locomotional structure, only a minute portion of the locomotional options lead to task-relevant destinations. Thus, even when not in desert fog, the user must repeatedly select among a large number of destinations, the vast majority of which are irrelevant to their task.

Lodestones and Leylines

The design implements a mechanical locomotional structure based on the task-defined locomotional structure described above. In order to retain the purported benefits of multiscale environments [2], the design retains the basic mechan-

ics of zooming and panning. However, as shall be seen, locomotion is constrained so that movement always leads toward a task-relevant destination. The system both predicts the destination and computes a path to that destination.

Destinations offered by the mechanical locomotional structure are called *lodestones* (since they "attract" navigational attention) to reflect their conceptual generality. In the present design, lodestones are, with one exception, single objects. However, in a generalized version of the design, a lodestone could equally well be a set of objects or some significant feature of the environment. Routes leading to lodestones are called *leylines* (named for the lines of power found in Celtic and Nordic folklore). In the present design, a leyline is a "straight" line through space-scale from the present location to a lodestone, but it could readily be defined to follow other dynamically computable trajectories.

In order to initiate movement, the user indicates the desired direction of zoom (in or out) by pressing the appropriate mouse-button (Figure 2:1). If zooming in, the system uses the mouse location to select the nearest lodestone (regardless of whether it is visible) as the predicted destination and computes and begins to zoom along the leyline that will center this lodestone in the view (Figure 2:1-3). Moving the mouse to be closer to a different lodestone during zoom-in changes the target prediction (Figure 2:2', 2). The system immediately detects the new destination and computes the new leyline to be followed. This allows easy error correc-
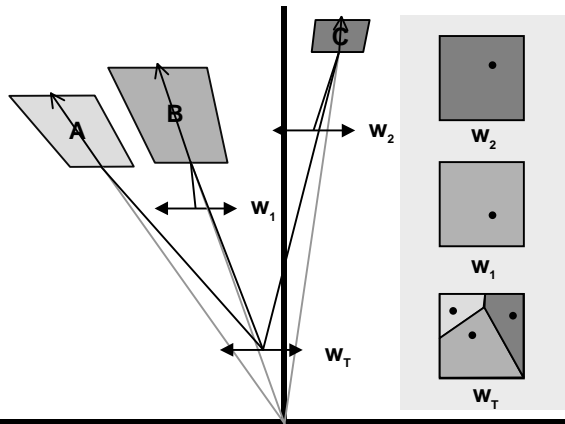
Figure 3 Zoom-in is constrained to follow a leyline (black arrows) to a lodestone. If there are multiple lodestones, the leyline that leads to the lodestone whose center (gray lines) is closest to the mouse location is followed. In w_T, as long as the mouse is anywhere in the light gray area zoom-in leads to **A**, in medium gray to **B** and dark gray to **C**. Zoom-in anywhere in w_2 leads to **B**, anywhere in w_1 to **C**.

Figure 4 Zoom-out is constrained to move toward, but not past, the Top of the [Lodestone] World (w_T). In the space-scale diagram, this is shown as dotted arrows. In the schematized views on the right, lodestone locations are indicated by dots. Zoom-out is possible from w_1 and w_2, but not w_T. Gray lines in the space-scale diagram show the defining boundaries of the Top of the [Lodestone] World. Leylines are computed dynamically, based on the current location.

tion and scanning of potential destinations. If no lodestone can be reached by zooming in, zoom-in is not permitted.

If zooming out, the destination is assumed to be a special lodestone, the *Top of the [Lodestone] World* view (Figure 2:1). This is the most magnified view that contains all lodestones in the world. Since no new lodestones can be brought into view by further zooming—i.e., further zoom-out would not lead closer to any lodestones—there is no point in zooming out further and zoom-out is not permitted. While not part of the task-defined locomotional structure, the Top of the World can be shown to be a key branch point.

In short, to get from one lodestone to another, the user either does a single zoom-in or a two-step zoom-out-zoom-in. If the desired lodestone is in the current view, the user need only click somewhere in its vicinity to follow the leyline that leads to it. If the desired lodestone is not in the current view, the user clicks anywhere to zoom out until it is in view, then clicks to zoom in. In either case, zooming ceases when no more lodestones can be brought into view. Once the desired lodestone is targeted, the user need not move the mouse again. This behavior is illustrated visually in Figure 2 and diagrammatically in Figure 3 (zoom-in) and Figure 4 (zoom-out). (See sidebar for explanation of space-scale diagrams.)

Leylines represent an aberrant zoom behavior. In spite of the use of zoom "in" and "out" to describe following leylines, leyline trajectories are generally composite zoom and pan movements. "In" and "out" merely denote the direction of the zoom component of movement. This is evident in Figure 3 and Figure 4, where leylines can be seen not to intersect the space-scale origin. Zoom-in leylines have two parts. The first part is a pan-zoom that centers the view on the lodestone, with the lodestone nearly filling the view in
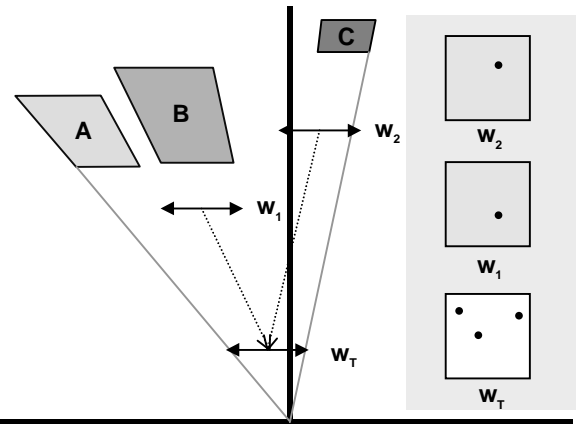
at least one dimension. (That this is reasonable scale of view is purely a design decision, based on the assumed task.) The second part is a pure zoom used once the lodestone is centered in the view. This two-part behavior is particularly evident in Figure 3 when following the leyline from view w_1 to lodestone **B**.

Lodestones and leylines locomotion makes systematic movement possible and provides the user with predictable movement in desert fog. The mechanical locomotional structure of lodestones and leylines is derived from the task-defined locomotional structure based on inter-object geometry. It offers far fewer destinations and routes than a mechanical locomotional structure based on the geometry of the space itself and, consequently, far fewer branch points with far fewer options at each.

Empirical Evaluation

Six subjects have, so far, taken part in a pilot study whose purpose is to examine the effect of locomotional design on wayfinding performance. The study is a 2 x 2 factorial within-subject design.

The first factor is mode of locomotion: leylines and Pad++. Subjects are alternately assigned to perform one or the other condition first to counter-balance possible order effects. Leylines mode uses lodestones and leylines described earlier. Pad++ mode uses the traditional model of locomotion also described earlier. The speed of zooming is identical in both conditions and the underlying computational time is roughly equivalent.

The second factor is the amount of wayfinding information provided: with wayfinding information and desert fog. In the with wayfinding informationcondition, some wayfinding information is always provided. In the desert fog condition, subjects are in desert fog unless a photograph is actually
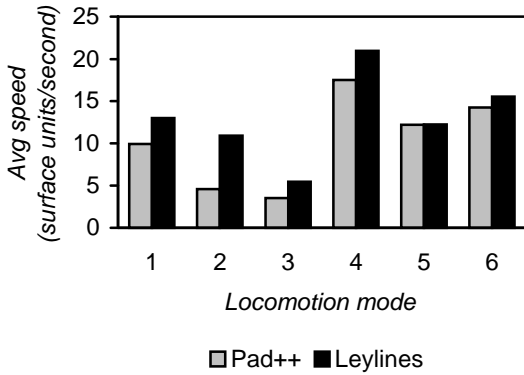
Figure 5 Average speed of movement for subjects in pilot study for condition with wayfinding information, paired by subject. t = 3.02 (p < .05).

visible in the window. The environments for the two conditions contain 50 and 5 lodestones (photographs), respectively. Subjects are asked to move from one lodestone to another in a given sequence, and timing data are collected.

Data from the six subjects tested consistently show improved performance in the leyline condition (Figure 5). A simple one-tailed paired t-test yields a value of t = 3.02 (p < .05) for the with wayfinding information condition. This analysis is based on average speed rather than absolute time as subjects used different layouts for the two conditions. In the desert fog condition, all subjects were successful on 5 out of 5 trials in leyline mode. Only one subject—chancing into an unusually compact layout—was able to complete the task in Pad++ mode. The remaining subjects succeeded on average 0.8 out of 5 trials before giving up.

These results are even more pronounced than expected and appear to be due to differences in the cognitive overhead of wayfinding and controlling movement. Subjects uniformly comment upon the reduction in effort they experience using lodestones and leylines. They perform visibly fewer physical actions in this mode, including less "stop and go" movement. The apparent groupings seen in Figure 5 do not correspond to ordering of mode of locomotion. They are conjectured to be due to individual differences in spatial ability—the three subjects (4, 5, 6) exhibiting less effect of locomotion mode (and higher speeds) had extensive experience as military or acrobatic pilots or in orienteering.

Discussion

This section has presented a locomotional design for a multiscale environment that supports wayfinding by constraining locomotion. The idea of constraining locomotion is not in itself novel. Like point of interest movement [15] and path drawing [9], lodestones and leylines uses an approximate indication of destination from the user to compute a path and guide movement along it. However, both these techniques require that the destination be in the current view and can only be used for localized movement.

Constrained Navigation [7] allows the target to be out of view and uses the structure of environmental features to guide locomotion but does not incorporate the notion of interactive target prediction. Guided Navigation [6] combines environmental structure and approximate indications of direction from the user to compute a path, but does not incorporate the notion of a destination. Both of these techniques reduce the number of branch points, but neither reduces the number of options at branch points.

FUTURE WORK

The present work has focused on the static mechanical locomotional structure. The main direction of future research is to develop the theory further, namely to include dynamic aspects of locomotional design. Work is in progress to understand how dynamic properties of movement—speed, steering controls, etc.—affect wayfinding complexity.

Additionally, the design example is being explored further. First, a full user study is in progress. Second, work is planned to explore hierarchical locomotion using spatial clustering of lodestones to determine composite lodestones. Third, the task of editing—modifying the contents of the space—needs to be explored in light of the theory. It is expected that a model constraining movement globally, but allowing unconstrained movement locally, e.g., near existing objects, will prove advantageous.

While lodestones and leylines was tested on an environment with only 50 lodestones, it is expected to generalize in several ways. First, there are many situations where the system, in practice, guarantees a small number of destinations. For instance, the system may present only a small set of destinations to the user, e.g., the typical user's desktop or a query result set. Or, the system may be able to predict likely destinations with some certainty—based on past activity, for example. Second, even in crowded spaces, providing feedback about the possible destinations of the user's current path is likely to be helpful. Of course, use in such spaces will require considerable computational optimization.

SUMMARY

This paper has introduced a partial theory of design for locomotion. This theory assumes that locomotion is a purposeful, directed activity and therefore always in service of the cognitive task of wayfinding. Using a model of wayfinding as a problem-solving and decision-making activity, the theory suggests that complexity of wayfinding reasoning is controlled, in part, by how closely the mechanical locomotional structure of the design matches the task-defined locomotional structure. And, in part, by how many decisions the mechanical locomotional structure requires from the user and how many options are offered for each decision.

Application of the theory to the task of moving between objects in a multiscale environment resulted in the lodestones and leylines design for locomotion. Using the task-defined locomotional structure, the design constrains locomotion based on inter-object geometry and uses an ap-

proximate indication of direction from the user to predict a target location and guide movement. Preliminary results of a pilot study indicate that this technique significantly improves wayfinding performance.

While the theory itself is still incomplete, it represents a new way of thinking about locomotional design as well as a new way of thinking about supporting design efforts. It encourages designers of locomotional techniques to include considerations of the wayfinding problem-solving and decision-making activity their design is likely to need to support and provides some guidance of how to do so. The theory also provides an example of a generative design theory that informs design prior to the specification of a particular design situation. The present theory does so by relating domain-specific concepts to design-specific features using preexisting domain knowledge. This approach to supporting design is distinct from work on design methodologies, design process support or methods for design evaluation in that it is aimed at informing design content rather than design process.

ACKNOWLEDGMENTS

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