STEERING IN LAYERS ABOVE THE DISPLAY SURFACE

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PERMISSION TO USE

ABSTRACT

Interaction techniques that use the layers above the display surface to extend the functionality of pen-based digitized surfaces continue to emerge. In such techniques, stylus movements are constrained by the bounds of a layer inside which the interaction is active, as well as constraints on the direction of movement within the layer. The problem addressed in this thesis is that designers currently have no model to predict movement time (MT) or quantify the difficulty, for movement (steering) in layers above the display surface constrained by thickness of the layer, its height above the display, and the width and length of the path. The problem has two main parts: first, how to model steering in layers, and second, how to visualize the layers to provide feedback for the steering task. The solution described is a model that predicts movement time and that quantifies the difficulty of steering through constrained and unconstrained paths in layers above the display surface. Through a series of experiments we validated the derivation and applicability of the proposed models. A predictive model is necessary because the model serves as the basis for design of interaction techniques in the design space; and predictive models can be used for quantitative evaluation of interaction techniques. The predictive models are important as they allow researchers to evaluate potential solutions independent of experimental conditions. Addressing the second part of the problem, we describe four visualization designs using cursors. We evaluated the effectiveness of the visualization by conducting a controlled experiment.

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DEDICATION

This work is dedicated to all my classmates and friends who were forced to drop out of school for reasons beyond their control, in a hope that there will be better opportunity for the generations to come.

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LIST OF ABBREVIATIONS

Abbreviation	
2D	Two Dimensional
3D	Three Dimensional
A	Amplitude - The Length of a Steering Tunnel
CD	Control Display
DM	Direct Mapping
H	Height of a Layer above the Display Surface
HCI	Human Computer Interaction
ID	Index of Difficulty
IP	Index of Performance
MT	Movement Time
ODM	Overview with Direct Mapping
OV	Overview
PDA	Personal Digital Assistant
PO	Partial Overview
SIT	Structural Information Theory
T	Thickness of a Layer
W	Width of a Steering Tunnel (Path)

CHAPTER 1

INTRODUCTION

Pen-based systems offer a number of advantages over the traditional mouse-based desktop metaphor, such as allowing for fluid input and the direct manipulation of underlying data. With the rapid development of display technology, such systems now come in many forms, and HCI researchers are designing interfaces for a variety of pen-based systems such as PDAs [10], Tablet PCs [9, 23, 31, 32], tabletops [59], and large displays [29, 47].

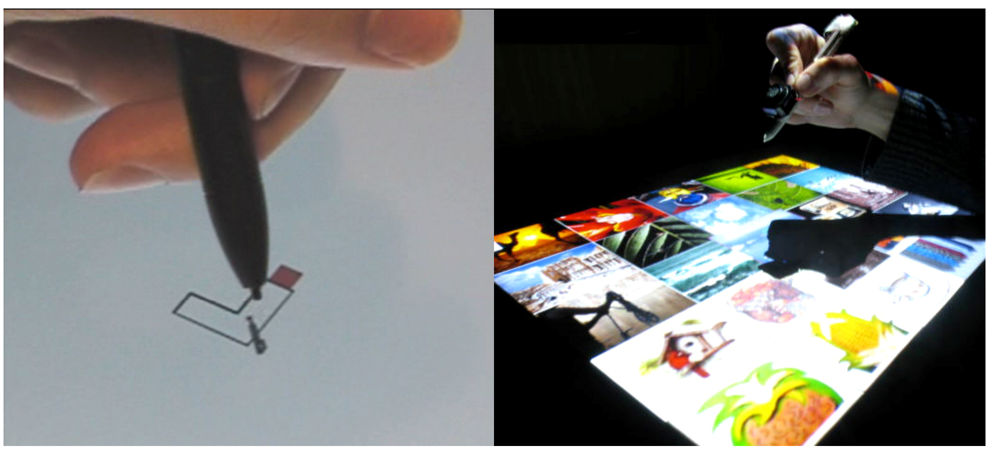

Figure 1.1. Above-the-surface interaction. (a) A Hover Widget [28] is used by making a gesture with the pen in the tracking state. (b) Multi-layer interaction [59] divides the space above a tabletop display into multiple interaction layers

Many such systems can also be called *digitized surfaces*, meaning they are able to sense the location of the input device even when it is above the display surface, that is, in the *tracking state*. Recent research has investigated how this tracking state can be used in the design of pen-based interaction techniques [12, 23, 28, 31, 59]. For example, Hover Widgets [28] allow users to invoke localized widgets by making gestures in the tracking state (Figure 1.1a).

The interactive area above the display surface is called an *above-the-surface interaction layer*. In many systems, there will only be one such layer; but in an increasing number of systems, there are multiple discrete interaction layers which allow for multi-layer interaction techniques [59] (Figure 1.1b).

While above-the-surface interaction layers increase the functionality of pen-based systems, they require users to steer the tip of the stylus through a constrained space. For example, if the layer is the tracking state, the stylus must remain above the display surface without touching the display, and not extend so far from the display surface that it is out of range. Currently, our understanding of human abilities to perform such a steering task is based on the Steering Law proposed by Accot and Zhai [1]. However, this model applies to a 2D desktop environment, and it is not clear if and how this model can be applied to user movements in above-the-surface interaction layers.

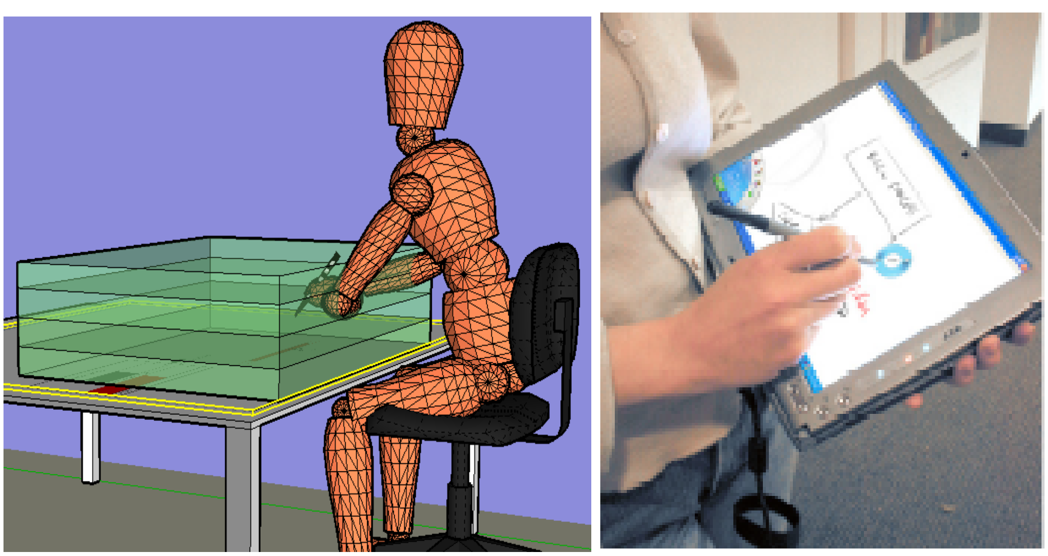

Figure 1.2. a) Multi-layered tabletop showing virtual boundaries. b) An interaction technique on a Tablet PC [23]

1.1 The Problem

The problem addressed in this thesis is that designers currently have no model to predict movement time (MT) for steering tasks constrained by thickness, width, and length of the path, in above-surface-interaction layers. The problem has two main parts: first, modeling steering in layers; and second, visualizing the layers to provide feedback for the steering task.

1.1.1 Modeling

Modeling steering in above-the-surface layers is based on steering in 2D, which is well understood. Steering in 2D is constrained by the width and length of the path. For example, navigating items in a cascading menu is an example of a steering task. However in above-the-surface layers, steering is additionally constrained by thickness of the layer (see Figure 1.2) as well as the height of the layer from the display surface. Thus the modeling problem is one of finding the relation between several constraints: the *length*, and *width* of the steering path, the *thickness* of the steering layer, the *height* of the layer from the display surface, and the *movement time* for steering tasks.

1.1.2 Layer Visualization

Interaction in above-the-surface layers involves moving within layers of certain thickness or moving up and down between the layers. This requires that users know which layer the pen is in and where in the layer the pen is positioned. For above-the-surface layer interaction to be effective, visualizations embodying this information as feedback have to be designed. The problem is one of visualizing three-dimensional input space on a two-dimensional display, giving feedback about the position of the pen. Apart from its use in experimental validation of the model for steering in layers, these visualizations can also be used in new interaction techniques for above-the-surface layers.

1.2 Motivation and Importance

This research presents a predictive model of movement time for steering in layers above the display. Predictive models are important as they allow researchers to evaluate potential solutions independent of experimental conditions. There are two reasons why a predictive model is necessary: first, the model serves as the basis for design of interaction techniques in the design space; and second, predictive models can be used for quantitative evaluation of interaction techniques.

In HCI research, user performance is measured using both qualitative and quantitative studies. Although more precise and reliable, there are very few quantitative tools available for researchers. If two experiments use different values for experimental parameters in measuring a predominant interaction, performance results of the two experiments can not be directly compared. Models such as Fitts' law and the Steering Law have been successfully applied to benchmark pointing and steering, two of the predominant interactions, demonstrating the usefulness of quantitative models as well as enhancing the quality of evaluations.

Thus it is necessary that a steering model specific to above-the-surface layers be derived, establishing the relation between the constraints affecting steering and the time required to steer. This model will enable comparison of the interaction techniques in above-the-surface layers even though the techniques are evaluated under different experimental conditions. The model also serves as the benchmark for the performance of new interaction techniques in above-the-surface interaction layers.

1.3 Solution and Validation

The solution is a predictive model of *movement time* for steering through above-the-surface interaction layers. We review Accot and Zhai's original 2D steering model and then show how this model can be extended and applied to steering through above-the-surface layers with an additional constraint: layer *thickness*. Through a series of four formal experiments we validate the derivation and applicability of the model. Further, we introduce the *height* constraint to study human capabilities when steering in layers positioned at different heights above the display surface. We extend the steering law to steering in above-the-surface interaction layers positioned at different heights above the display, and derive a model based on the steering law and its variants. The proposed model is validated by conducting a controlled experiment. The application of the results of the experiments to the design of above-the-surface pen-based interaction systems is discussed.

Any layer-based interaction technique that uses these models must also provide feedback. Traditional 2D desktops use cursors to give feedback about various aspects of the interaction. For example, in painting applications, the cursor is used to indicate the type of tool in use. Using a similar approach, we visualize above-the-surface input space and the input state of the pointing devices using cursors. We study several cursor designs for the above-the-surface design space and present a quantitative analysis of their performance.

These studies provide a tool to compare the performance of applications in above-the-surface input space. These studies also open several questions, such as the possibility of a generalized model for steering in curved tunnels, and the effect of motor and visual space expansion in multi-layer visualization.

1.4 Steps in the Solution

This research provides a solution to the problem in three steps. First, a model to predict the movement time for steering in layers immediately above the display is derived and validated. Second, the model is extended to predict movement time for steering in layers positioned at different heights from the display. Lastly, different layer visualization designs are studied using controlled experiments and implications for visualization design for above-the-surface interaction layers are discussed.

1.4.1 Modeling Steering within Above-the-Surface Interaction Layers

The above-the-surface steering model is derived in four steps. To begin with, Fitt's law and the Steering Law are applied to interaction in layers where the only constraint is *thickness*. Subsequently, the bivariate pointing model by Mackenzie and Buxton [42] is applied to incorporate the *width* constraint. Application of *width*, *length* and *thickness* constraints in effect makes the task a steering task inside a 3D tunnel positioned immediately above but not touching the display. The model for steering within above-the-surface layers is validated by controlled experiments. Experiments recorded the movement time for interaction under different constraints. Recorded movement time values were correlated with the values predicted by the derived models. The high correlations show that the models are valid.

1.4.2 Modeling Steering within Layers at Different Heights above the Surface

The *height* of the layer from the display surface becomes a constraint when layers are positioned at different heights above the display surface. The height constraint is incorporated into the model based on the bivariate pointing model of Mackenzie and Buxton [41]. This model is capable of predicting movement time for steering in tunnels above the surface, and is validated by a controlled experiment. There is a high correlation between recorded values for movement time and the values predicted by the derived model.

1.4.3 Above-the-Surface Layer Visualization Using Cursors

The final part of the solution provides designs and empirical evidence as to which visualization is most appropriate for multilayer input space. Four different visualizations are designed using cursors, and their performance in tasks involving switching layers is studied through a controlled experiment. The study shows that: direct mapping of input and output allows faster interaction, users prefer direct mapping of input and output closely followed by a visualization that combines an overview and direct mapping, and the visualization that also provides an overview has stable error rates across layer thicknesses.

1.5 Contributions

This research makes three main contributions:

- A model to predict movement time for steering in above-the-surface interaction layers.

- A model to predict movement time for steering in layers positioned at different heights above the display surface.
- Evaluation of designs for visualizing the position of the pen in layers above the display surface.

Other contributions of this research include:

- Design recommendations related to upper and lower limits for tunnel *lengths*, *thickness* and *height*, in above-the-surface input space, for interactions involving steering and layer switching.
- Design recommendations related to, Control to Display ratio for layer switching interaction in above-the-surface interaction layers.

1.6 Thesis Outline

Chapter 2 of the thesis reviews literature related to layered interaction, models of pointing and steering performance, and layer visualization. Layered interactions are surveyed followed by approaches to modeling interactions in different input spaces. Reviewing related work in layer visualization, the use of cursors in visualization is discussed, followed by perception of motor and visual space. Review makes observations which need to be considered when designing visualization for above-the-surface layers.

Chapter 3 contains derivations of the models and their validation. First, the model for steering in above-the-surface interactions is derived based on certain assumptions. Then four different experiments are described that validated the assumptions, and the model for steering in above-the-surface is explained. Second, the model for steering in above-the-surface layers positioned at different heights above the display is derived. Then the design and results of the experiment to validate the model are explained.

Chapter 4 presents the design of layer visualization. The layer visualization design process is explained followed by the illustration of the controlled experiment studying the designs. Four different designs are examined. This is followed by the description and results of the experiment which studies these designs.

Chapter 5 discusses the results of the validation of the models as well as the visualization designs. The observations made in experiments are discussed so that they can be incorporated to design applications in above-the-surface interaction layers. Then the implications of the study are described, starting with the steering model for above-the-surface followed by the steering model for above-the-surface positioned at different height above the display. Lastly, comparison of the layer visualization designs and its impact on visualization design is presented.

Chapter 6 summarizes the findings in the research followed by a discussion of topics for further research, including possible improvements to the models and visualization designs, and limitations of the models presented in this thesis are discussed.

CHAPTER 2

RELATED WORK

The review of related work is divided into four sections. First, pen-based systems and work related to pen-based interaction is reviewed. Second, interaction techniques for above-the-surface layers are discussed. Third, we explain previous efforts to model human performance, in both pointing and steering tasks. Finally, we review research related to layer visualization, perception of motor and visual space, and mapping of motor space to visual space.

2.1 Pen-Based Interaction

Pen-based systems use a stylus to interact directly with the display surface. The RAND Tablet developed in 1964 was the first pen input device [16]. In the RAND Tablet, a pen was used to interact with a tablet which in turn controlled the position of cursor on a CRT monitor. Sketchpad, developed by Ivan Sutherland, also enabled direct interaction with the display using a pen [60]. Using Sketchpad, users could draw directly on the display. As technology improved and also became more affordable, pen-based interaction has become more prevalent. PDAs, Tablet PCs, tabletops, and large displays are some of the current examples of pen based systems.

Researchers have invented many techniques to enable and improve pen-based interactions. We review some of the techniques for invoking menu items, selecting objects, and moving objects, on the display using a pen.

Marking Menus are a technique to select a menu item not only by invoking a localized menu but also by gesturing on the display in the direction of the required menu item [39]. Tracking Menus [23] stay under the pen cursor and close at hand, aiding activation of menu items. The user can reposition the menu by dragging past its edges.

Radar View is a technique that creates a miniature of the large display. When the users select an object in the miniature view using a stylus, the corresponding object in the large display is selected [57, 56]. Tractor Beam is a hybrid point-touch interaction technique that facilitates reaching distant objects on a large tabletop. With this technique, users can select distant objects on a tabletop by casting an invisible ray from the tip of the stylus [49].

The Drag-and-Pop technique helps in moving objects on the display [15]. When an object is dragged, proxies of objects in the direction of the drag are created close to the user. The proxies maintain the original spatial order, making the selection of the destination folder easier. Agrawala et al. [5] demonstrated Bumptop, a desktop organization structure optimized for pen input. Bumptop is a physically realistic virtual desktop that uses piles in place of folders. Objects in the virtual desktop simulate the real world effects such as friction and mass.

2.2 Above-the-surface Interaction

In many pen-based devices, space immediately above display is used to interact with the device. Interaction is active as long as the pen is within certain distance from display where state of the pen is tracked. Many pen-based interaction techniques use the tracking state of the pen to provide added functionality [10, 12, 23, 31, 28]. Most of the techniques require users to move a pen within the above-the-surface interaction layers without any *width* or *length* constraints. For example, the Vacuum [12] is a technique that supports reaching distant objects on a large display with a pen. By moving the pen within the tracking state, the Vacuum widget can be used to interact with multiple objects. Exiting the layer into the out-of-range zone dismisses the widget. Stitching [31] uses pen gestures that span multiple displays to seamlessly connect displays for co-located collaboration. Users stitch displays by moving the pen across the displays while keeping the pen in the tracking state. Tracking menus [23] are menu widgets that stay under the pen cursor and are therefore close at hand. The user can reposition the menu by dragging past its edges while in the tracking state.

Multi-layer interaction techniques [59] divide an enlarged tracking state into multiple interactive layers. Users can navigate within individual layers to access different tools, and perform various commands (Figure 2.1).

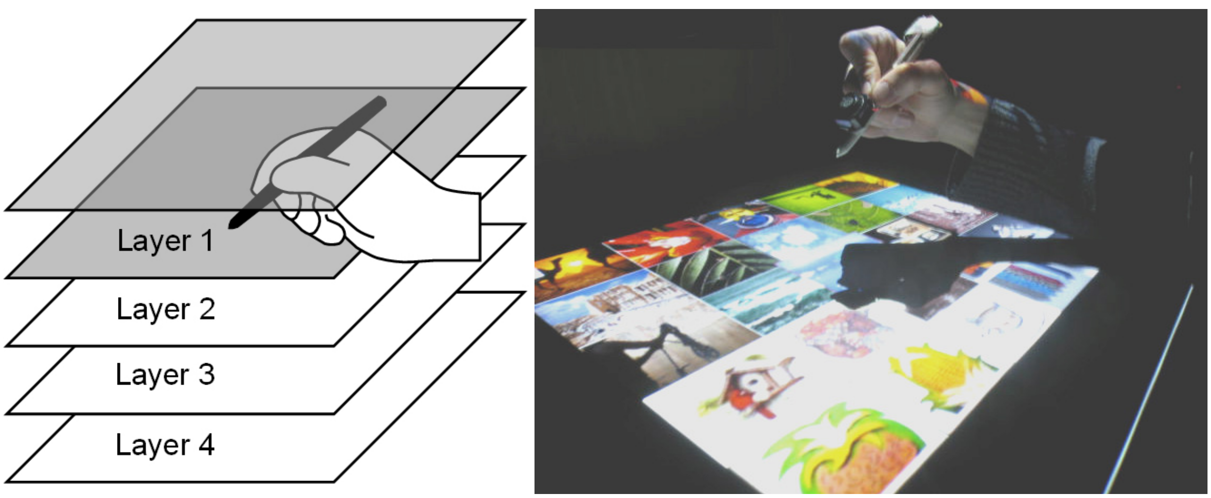

Figure 2.1. Multilayer interaction technique with a schematic diagram of layers

Hover Widgets [28] are an example of a technique which requires users to not only navigate within the tracking state, but to do so under imposed directional constraints. Gestures, defined by tunnels, are made in the tracking state to quickly access localized interface elements.

In summary, a number of techniques use above-the-surface interactive layers, and require users to navigate within them. Despite this, there is little understanding as to human capabilities when performing such a task. We now discuss related modeling techniques which will help us obtain a better understanding.

2.3 Modeling Pointing and Steering

We review predictive models for pointing followed by predictive models for steering. We begin by discussing the original model for pointing and corrections proposed to the model. We complete the review by explaining the work related to modeling of steering actions.

The derivation of Accot and Zhai's steering law is based on Fitts' law, which models pointing [22]. The law states that pointing performance is limited by the capacity of the human motor system. The commonly used form of Fitts' law [41] predicts the movement time MT to select a target of width W at a distance of A as follows:

$$MT = a + b\log_2\left(\frac{A}{W} + 1\right) \qquad (2.1)$$

where a and b are empirically determined constants specific to an input device. The logarithmic term is called the index of difficulty (ID).

Mackenzie and Buxton [42] extended Fitts' original model for a 2D target acquisition task. They examined several formulas for the index of difficulty for a rectangular target of width W and height H, and found the *min model*, which only considers the smaller of the two dimensions, to have the highest correlation with their experimental data. Addressing some of the difficulties associated with the min model, Accot and Zhai later refined this model into a weighted Euclidian model, expressed by:

$$MT = a + b\log_2\left(\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{H}\right)^2} + 1\right) \qquad (2.2)$$

where η is empirically determined. The addition of the parameter η allows the model to weight the effect of the height differently from the effect of the width. Figure 2.2 shows the variables in the Equation 2.1. Figure 2.3 shows the change in ID corresponding to change in the variables.

Figure 2.2. Variables in the bivariate pointing model

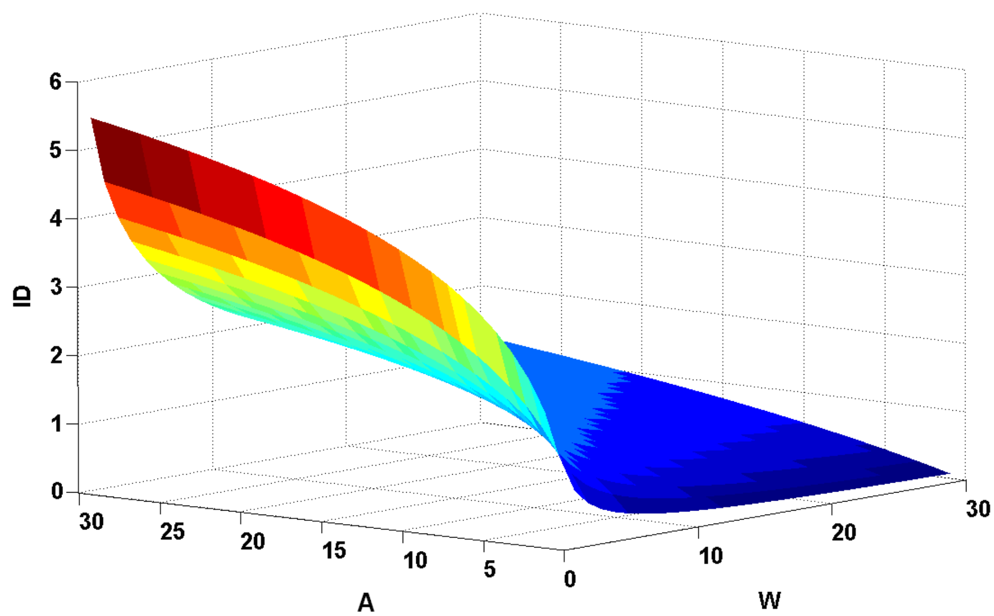

Figure 2.3. Width and Distance by ID for the Bivariate Pointing Model

Another task prominent in graphical user interfaces is steering, or tunneling, which can be described as the task of moving through a constrained path, such as when a user navigates through hierarchical cascading menus [4]. To derive a model for this task, Accot and Zhai [1] first consider a goal crossing task, where a user must travel a distance A, and then cross a goal with width W. They found that this task can be accurately modeled with Fitts' Law (Equation 2.1).

Based on this initial study, they derived a model which predicts the time necessary to steer through a path. In the most basic case, the path has a constant width, *W*, and length, *A*. The law is derived by considering the task to be an infinite series of goal-crossing tasks [1]. The resulting model reduces to:

$$MT = a + b\left(\frac{A}{W}\right) \tag{2.3}$$

where a and b are empirically determined constants *A* is the distance between the goals and W is the width of the goals. Figure 2.4 depicts variables in steering with a width constraint. Figure 2.5 shows the change in ID corresponding to change in the variables *A* and *W*.

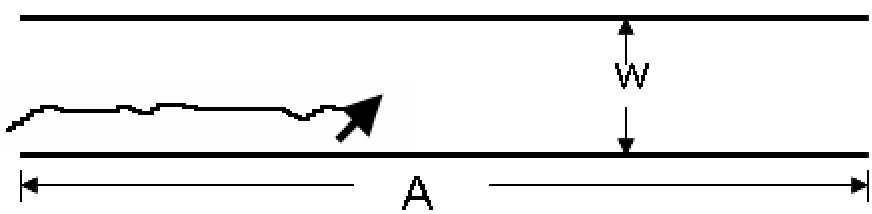

Figure 2.4 Steering in a path of width W and length A

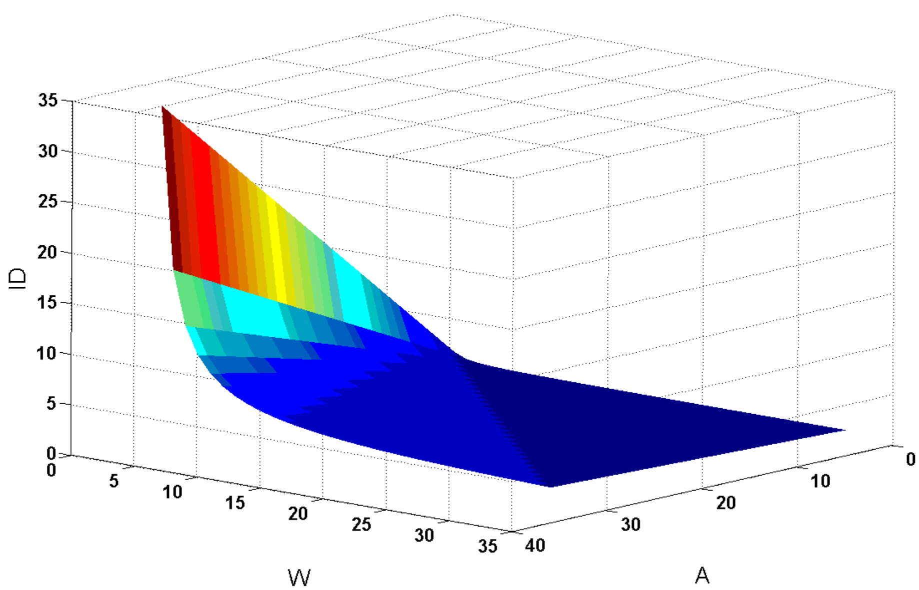

Figure 2.5. Width and Distance by ID for the 2D Steering Model

In the more complex version of the task, the path width varies along its length. In this case, the task can be modeled by the equation:

$$MT = a + b\int_C \frac{ds}{W(s)} \qquad (2.4)$$

where C is the path and $W(s)$ is the width of the path at point s [1]. Follow-up studies have investigated the effects of scale [2] and sharp corners [50] on the steering task.

One contribution of Accot and Zhai's original steering law work is that it has been used to model actual user interface tasks [6, 30]. The original work has also inspired new interaction techniques [3, 9]. Grossman and Balakrishnan [26] propose a model for trivariate pointing. It adds to the existing perspective in that it considers the orientation of the targets. Their model is given by:

$$ID_{WtEu\theta} = \log_2\left(\sqrt{f_W(\theta)\left(\frac{A}{W}\right)^2 + f_H(\theta)\left(\frac{A}{H}\right)^2 + f_D(\theta)\left(\frac{A}{D}\right)^2} + 1\right) \qquad (2.5)$$

where θ is the movement angle formed by the axis horizontal to the user and the line from the target to the starting point and W, H, D are the dimensions of the target. $f(\theta)$ is function whose value is dependent on the movement angle θ. A is the distance to the target. It should be noted that the effect of the height of the target compared to the resting position of the hand has some role to play in pointing and steering. We elaborate on this in a context specific to steering in layers when the derivation of our model is discussed in Chapter 3.

2.3.1 Other Formulations

All the models discussed so far are derived from the perspective of information theory. There are similar formulations in Biophysics which bring different perspectives to performance modeling. The earliest known model for steering is given by Rashevsky [54]. In 1959 Rashevsky modeled the maximum possible velocity V of a vehicle being steered on an empty highway. His model is given by:

$$V = \frac{S - S^{\circ} - 2\delta - \theta l^{\circ}}{\theta\tau} \qquad (2.6)$$

where τ the reaction time of driver, S is the width of the path S^{o} and l^{o} are width and length of the car, δ is the minimum safe distance of the car from the edge and θ, the average angle by which the direction of car sometimes deviates from the true course. Figure 2.6 shows different parameters in the Equation 2.6. It can be shown that this reduces to Accot and Zhai formulation when S, S^{o}, l^{o}, δ , θ are ignored [1].

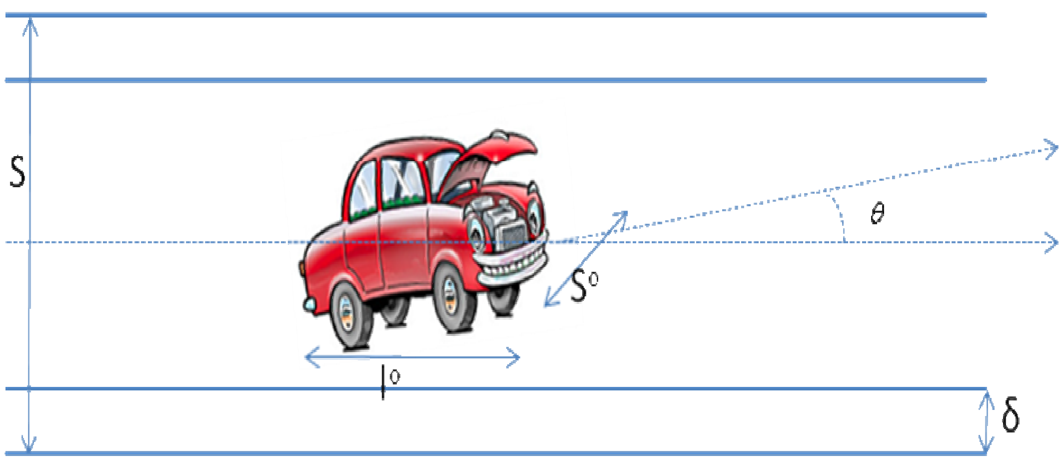

Figure 2.6. Variables in Rashevsky steering model [54]

C. G. Drury, in 1971, working on the problem of the drawing task with a lateral constraint, derived a model to predict t_l, the time required to move a distance l with the width of the tolerance zone being T [18]. The model is given by:

$$t_l = \frac{l k_1 k_2 t_0}{T} \qquad (2.7)$$

where k_1,k_2, are constants and t_0 is the sampling interval of position. It can be shown this can be reduced to the Accot and Zhai formulation when k_1,k_2 and t_0 are ignored [1]. Although the Drury and Rashevsky models incorporate more variables, their application to HCI remains unexplored. Therefore we base our research on the formulations of Accot and Zhai, which have been successfully applied to model steering tasks in HCI.

2.4 Layer Visualization Using a Cursor

We review the research related to layer visualization in three sub-sections. We discuss previous work on the use of cursors for visualization, followed by previous studies on perception of motor and visual space. We then explore previous work on mapping of motor space to visual space (CD ratio) in the context of visualization of layers in above-the-surface interaction.

2.4.1 Cursors in Visualization

Cursors are used to visualize aspects such as the state of an application and characterization of participants. Muller introduced multifunctional cursers for direct manipulation user interfaces [19, 48]. In his interface, the cursor not only indicated the position of the mouse but also provided clues about the state of applications. For example, the cursor could visualize a selected menu item, reducing the cognitive load in remembering the state of the application. Figure 2.7 shows a screen shot of a paint application highlighting the cursor (shown in red rectangle) visualizing the color picking tool.

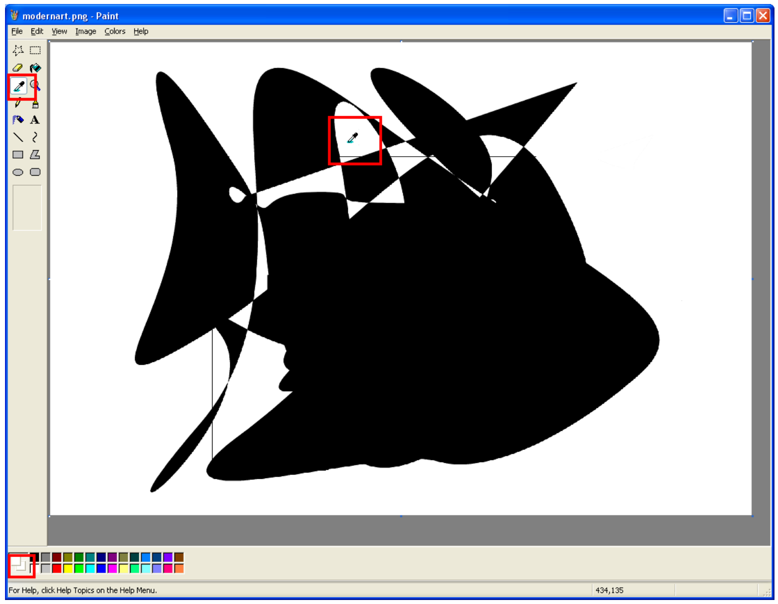

Figure 2.7. Screen shot of a paint application highlighting the color picking tool

More recently, it has become a common practice to use different types of multifunctional cursors in graphical user interfaces. The Spider cursor, designed to interact with 3D surfaces further expands the functionality of cursors [46]. The cursor has the shape of a spider and runs on top of the 3D surfaces, facilitating perception of neighboring data points. The legs of the spider align themselves with edges of the 3D surface, allowing better identification of the local properties of the shape. Another use of cursor for visualization can be seen in the Silk Cursor [68]. The Silk Cursor introduces a semi-transparent volumetric cursor to enhance depth cues to aid 3D target acquisition. A study showed that volume and occlusion cues provided through cursors improve 3D target acquisition [62]. Studying the role of cursors in groupware, Greenberg et al. [25] overloaded cursors with semantic information. They found that semantic overloading enhances awareness among the participants. Taking this further, Stach et al. [58] show that rich embodiments can improve characterization and recognition of participants in a groupware system. One study successfully demonstrates the use of cursors to visualize thirteen information variables. Figure 2.8 shows an example of rich embodiment.

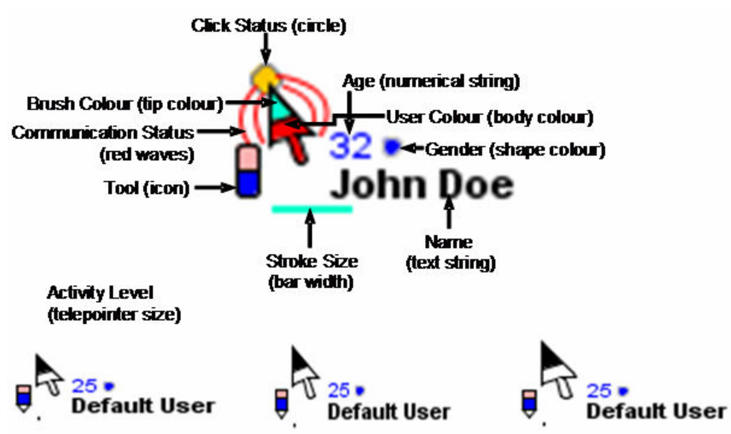

Figure 2.8. A cursor embodying information variables such as Name, Age, Gender, Brush Color [31]

Visualizations using the cursors discussed so far are either for traditional desktop systems or systems that have input space similar to desktop systems. Hence, they can not be directly incorporated to 3D pen input devices and to above-the-surface interaction layers. Nevertheless, the idea of reducing cognitive load, increasing awareness by semantic overloading, and mapping cursors to underlying objects can be borrowed.

Physical layering of the input space above the display was introduced by Subramanian et al. [59] through the Multilayer interaction technique. Multilayer interaction divides the input space of a tabletop into discrete horizontal layers. To enable interaction, the prototype of Multilayer interaction uses a rectangular cursor to visualize the layer in which the pen lies. The upper and lower halves of the rectangle are filled with red, yellow or green depending on whether the pen is drifting above or below a layer. However, this is a limited visualization where only one layer is visualized, and does not give either an overview of all virtual layers or show the position of the pen within a layer.

Pressure Widgets [53], while presenting a comparison of different pressure techniques, proposed several visualizations using the cursor. The designs for Pressure Widgets couple pressure levels to a distinct visual element in the cursor. The authors suggest that directly mapping pressure levels to a grid layout reduces interferences. Pressure input space is similar to above-the-surface interaction layers in that pressure levels can be considered virtual layers. We note that the pressure input space is completely virtual. However, above-the-surface interaction input space exists physically. Nevertheless, the cursor designs seen in Pressure Widgets successfully demonstrate the use of cursors in visualizing a dimension of input space.

2.4.2 Perception of Motor and Visual Space

Two spaces are involved in interacting with above-the-surface layers. They are *visual space* and *motor space*. Visual space consists of all display elements that aid visual perception and provide feedback for the user's actions. Motor space is the physical space used to provide input to the pen-based system. In pen-based systems, motor space is actually the input space on the display as well as the space above the display. When a user provides input by moving a pen in motor space, feedback is observed on the display (visual space). A task where feedback is used to continually decide the next state of the task is called a closed-loop task. Two types of distance estimations considered in visual perception are egocentric and exocentric distance estimations. The user's estimation of the distance to an object is called egocentric distance estimation (absolute distance from self). The user's estimation of the relative distance between two objects is called exocentric distance. In this section, we review previous research to understand the perception of motor space and visual space.

Previous research shows that feedback plays an important role in visually guided action [51]. It has been suggested that humans have two visual pathways: vision for action and vision for perception [45]. It is also proven that vision for action is more accurate, and that controlling hand movements is based heavily on binocular cues [40]. There is evidence to show that even in the absence of several important cues such as occlusion and relative size, retinal motion (binocular cues) may be used to estimate egocentric distance [43]. Thus, integration of visual cues for action and distance estimation is based on both visual feedback and the action that is based on the feedback. Studies have shown that the organization of perceptual motor space is considerably biased by visual cues [51]. This emphasizes the role of cues in the use of visualization to guide action. Thus previous research highlights the importance of the structure of information in the design of visual feedback for closed-loop tasks and the importance of mapping movement in motor space to corresponding changes in visual feedback [37, 43]. The structure of information is studied under the field of study called Structural Information theory (SIT) [34]. SIT is a theory of perceptual organization, emphasizing the perceptual information content in visualization rather than on the measurable information. A proven idea, central to SIT is the principle of simplicity, implying that the visual system prefers the simplest interpretation of all possible interpretations of a stimulus. Thus, it is imperative that the design for visualizing above-the-surface layers should choose a structure to organize information consistent with the simplicity principle.

We are interested in exocentric distance judgments in the closed-loop task of navigating within and between above-the-surface layers. Distance judgment in our research means the estimation of distance from the display to a target in the above-the-surface layers. Research on distance judgment suggests that issues in egocentric judgments, as discussed above, such as the importance of visual feedback and mapping for motor and visual space, will also be similar for exocentric distance judgments [2].

Another important aspect to consider is the perception of objects on horizontal displays such as tabletops. Perception of results of comparison in horizontal displays is shown to be more accurate for graphical variables lateral length, upright length and position, than other graphical variables [65]. This suggests that visualization of above-the-surface layers should use these variables to improve the efficiency of visual cues.

2.4.3 Mapping Motor Space to Visual Space

Mapping motor space to visual space refers to the coupling between movements in motor space and movement in visual space. The ratio of the amount of movement in motor space (control space) to the amount of movement in visual space (display) is called the Control Display ratio (CD ratio). CD ratios are represented in various ways such as using decimal fractions (0.5) and ratios (1:2). We use the ratio notation to represent CD ratios in the thesis. For example, an equal amount of movement in visual space for the same amount of movement in motor space will be represented as 1:1 ratio and the mapping will be referred to as the direct mapping or CD ratio without gain. Similarly, if the movement in visual space is double the amount of movement in motor space, the CD ratio will be 1:2 and we refer to it as CD ratio with gain. On a large pen-based digital table any CD ratio other than 1:1 (CD ratio with gain) would mean that the cursor on the display will move an amount lesser or more than the pen movement.

Previous research on pen input has investigated different CD ratios to map motor space to visual space [27, 13]. We know that the index of difficulty for pointing is determined by variables in motor space. Studies have shown that magnification of either motor or visual space (or both) yields improvements in performance [14, 44]. Because magnification of visual or motor space can be interpreted as a change in CD ratio, we can conclude that changes in CD ratio can improve performance. However, there is no agreement in the literature as to which type of CD ratio is best for pen based interactions. Design recommendations for interaction in large displays are in favour of CD ratio with gain (For example, CD ratio of 1:2) [33]. The Radar View technique applies CD ratio with gain to map motor space to Cartesian coordinates and is proven to be better than other techniques [7]. However, Gutwin et al. [30] show that a CD ratio without gain is better for large steering tasks. The approach adapted in the Steady Click [63] technique may be interpreted as considering the end of the CD ratio continuum. Steady click changes CD ratio to infinity (1:0) by stopping cursor movement in visual space when the cursor is on the target. Similar dynamic CD ratio approaches, where CD ratios are varied in time, have proven to improve selection performance [27].

Thus the *structure of information*, representation of *overview and detail*, and *CD ratio* need to be investigated to come up with an efficient design to visualize above-the-surface layers. In Chapter 3, the newly proposed predictive models for above-the-surface interaction are presented, which are validated in a series of four formal experiments. The design and evaluation of visualization techniques for above-the-surface layers are explained in Chapter 4.

CHAPTER 3

MODELING STEERING IN LAYERS

In this chapter predictive models for steering within above-the-surface interaction layers are derived and are experimentally validated. We begin with a derivation of the predictive model for steering in layers which are immediately above the display. After experimentally validating the initial model, we extend it to layers above the display at different heights, to arrive at the general model for steering within above-the-surface interaction layers.

3.1 3D Steering Model

The first task which we model is navigating within an above-the-surface layer, where the only constraint is the *thickness* of the layer. Examples of this scenario are seen in interaction techniques where the input device must stay within an above-the-surface layer while traveling from one point to another [12, 31]. We define the size of the layer, or *thickness*, *T*, as the distance between the bottom and top planes which define the layer. Figure 3.1a illustrates the task.

To derive a model for this task, we first consider the analogous goal crossing task, in which the goal is defined as a plane perpendicular to the display surface, extending from the bottom to the top boundaries of the layer (Figure 3.1b).

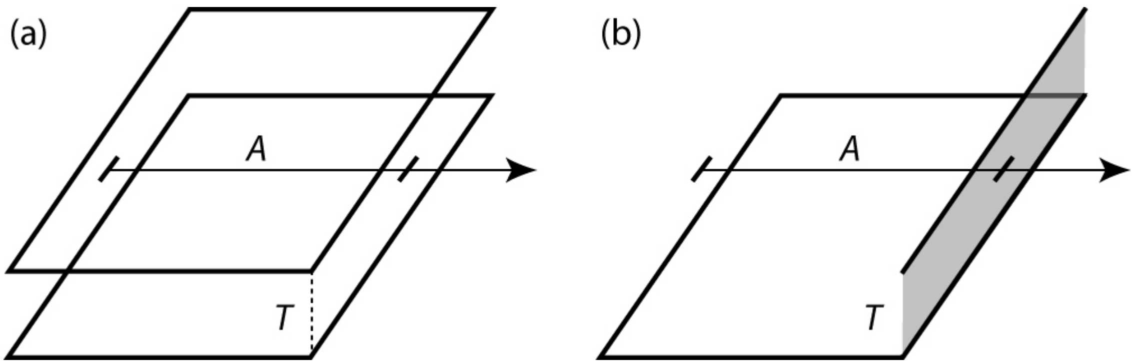

Figure 3.1. (a) Steering through a layer, constrained only by the layer thickness, *T*. (b) The analogous goal crossing task

We hypothesize that this task will be modeled by Accot and Zhai's original goal crossing formulation, where we simply replace the width variable with our thickness variable *T*. This gives the equation:

$$MT = a + b\log_2\left(\frac{A}{T}+1\right). \qquad (3.1)$$

Assuming this model does accurately model the goal crossing task depicted in Figure 3.1b, then it is reasonable to assume that the tunneling task depicted in Figure 3.1a, can be derived using Accot and Zhai's method, which would give the following model:

$$MT = a + b\left(\frac{A}{T}\right). \qquad (3.2)$$

A more complex scenario is navigating through a tunnel within a layer, where the movement is constrained not only by the layer thickness, *T*, but also by a path which is imposing a directional constraint, *W*. An example of this scenario is seen when the user activates a Hover Widget [28], as the input device must make a specific gesture, defined by a tunnel, in the display's tracking state. In this case, the size of the tracking state defines the layer thickness, and the width of the tunnel defines the directional constraint. Such a task is illustrated in Figure 3.2a.

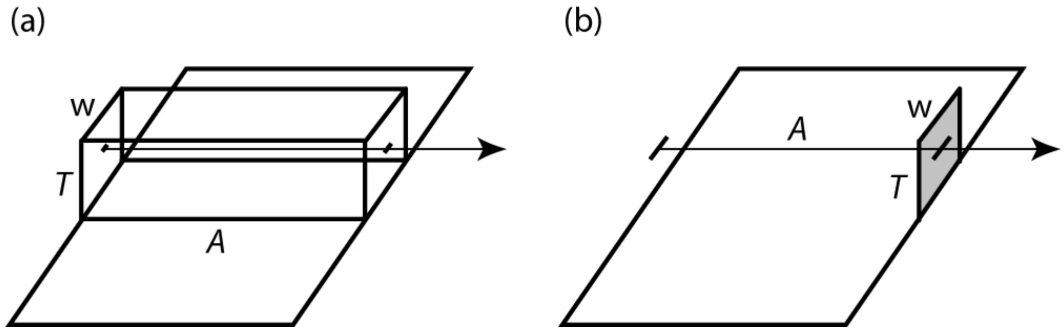

Figure 3.2. (a) Steering through a layer, constrained by the layer thickness, *T*, and the directional constraint of the path, *W*. (b) The analogous goal crossing task.

To derive a model for this scenario we again consider the analogous goal crossing task, in which the goal is defined by a rectangle, perpendicular to the display surface, with a height *T*, and width *W* (Figure 3.2b). It is interesting that we now have a bivariate, or two-dimensional, goal crossing task. Such a task has never been studied before, but we hypothesize that it can be modeled as a bivariate pointing task. We use the Euclidian model for bivariate pointing (Equation 2.2) to derive the following model:

$$MT = a + b\log_2\left(\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{T}\right)^2} + 1\right). \qquad (3.3)$$

Under the assumption that this model can accurately predict movement times for the 2D goal crossing task, depicted in Figure 3.3b, we can use it to derive a model for the 2D tunneling task depicted in Figure 3.3a. We again use the same methodology presented by Accot and Zhai [1]. We first break the tunneling task into a series of *N* goal crossing tasks Figure 3.3.

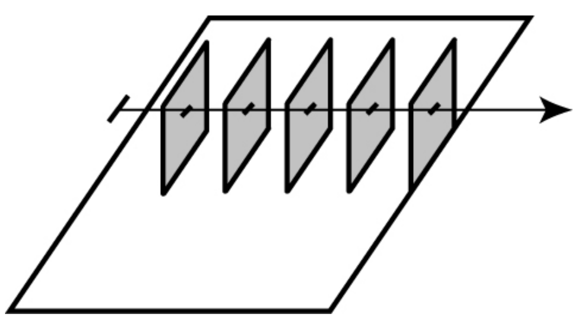

Figure 3.3. A series of goal crossing tasks

By summing the associated *ID* values for each of these *N* tasks, which have distances of *A/N*, we get:

$$ID_N = N\log_2\left(\sqrt{\left(\frac{A}{NW}\right)^2 + \eta\left(\frac{A}{NT}\right)^2} + 1\right) \qquad (3.4)$$

As *N* approaches infinity, the task becomes the desired 2D tunneling task. To obtain the index of difficulty for this tunneling task, we take the limit of ID_N as *N* approaches infinity. Using a first order Taylor series expansion of $\log_2(1 + x)$, we obtain:

$$ID = \lim(N \to \infty) ID_N = \frac{1}{\ln(2)}\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{T}\right)^2} \qquad (3.5)$$

These lead to our model for the movement time as:

$$MT = a + b\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{T}\right)^2} \qquad (3.6)$$

This is the model to predict movement time for steering in above-the-surface layers when the layer is immediately above the display.

3.2 Validating the Model

In the following sections we describe a series of experiments, with the goal of understanding human capabilities when navigating within above-the-surface interaction layers. In doing so we also validate the proposed models presented here.

3.2.1 Apparatus for all Experiments

All experiments described below were performed on the same apparatus. The experiments ran on an Intel Pentium 4 CPU 3.20 GHz PC with 1 GB RAM. Participants sat at a 124.5x158 sq.cm tabletop surface. A 1024x768 pixel image was projected onto the surface using a ceiling mounted projector. Figure 3.4 shows the apparatus.

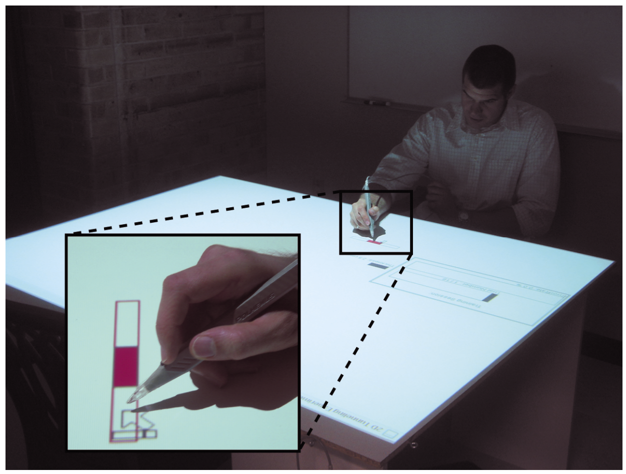

Figure 3.4. Apparatus used for the experiments

The system used in the experiments in this research is a pen-based digital table that uses the Polhemus 3D motion tracking system. The system consists of a projector that projects the computer display on a table and a 3D motion tracker that tracks the position of the pens on and above the table. 3D motion tracking works by calculating location, orientation, and positioning information relative to coordinate system whose origin is an electromagnetic pulse generator, placed below the table. A motion sensor emits electromagnetic pulses. Both the strength of the pulse and attenuation of the strength of the pulse with distance are known. These values are used to calculate position and orientation of the pen [33]. XYZ co-ordinates calculated from the pen are used to interact with the projected display.

A stylus was used for input, and was tracked using the Polhemus Liberty Motion Tracker. The motion tracking system provided positional data at a rate of 240 Hz. The pen was calibrated to report X and Y values in pixels on the tabletop surface, and Z values in centimeters. Z values correspond to the height above the tabletop surface. All users were seated comfortably and controlled the pen with their dominant hand. Users were allowed to rest their hand while completing the task, much like the hand rests while writing with a pen. The pen controlled the displayed cursor position using a direct 1 to 1 mapping. In all experiments the bottom of the layer was 0.2cm above the display surface.

3.3 EXPERIMENT 1: A Pilot Study of 1D Goal Passing

In this experiment we investigate a goal passing task, where the goal to be passed is a vertical region extending above the display surface. The experimental parameters will be the thickness of this region, or layer, and the distance between the goals which are to be passed.

We do not see this as being a task which will normally be carried out in pen-based interfaces. The reason for the experiment is for theoretical purposes, as the derivation of our model of the more applicable tunneling task is based on the model for this task. As such, we only ran two participants through this experiment, enough to ensure that the movement times will follow our proposed model (Equation 3.1).

3.3.1 Participants

Two volunteers (both male), aged 18 and 19 participated in the experiment. Both participants were right handed and controlled the stylus with the right hand. None of the subjects had previous experience with using large digital tables. Both subjects were tested individually.

3.3.2 Procedure

The goal passing task was accomplished by passing a start goal and an end goal, from left to right. Each goal was depicted as a vertical red line spanning the display, separated by a distance of *A* (Figure 3.5a and 3.5b).

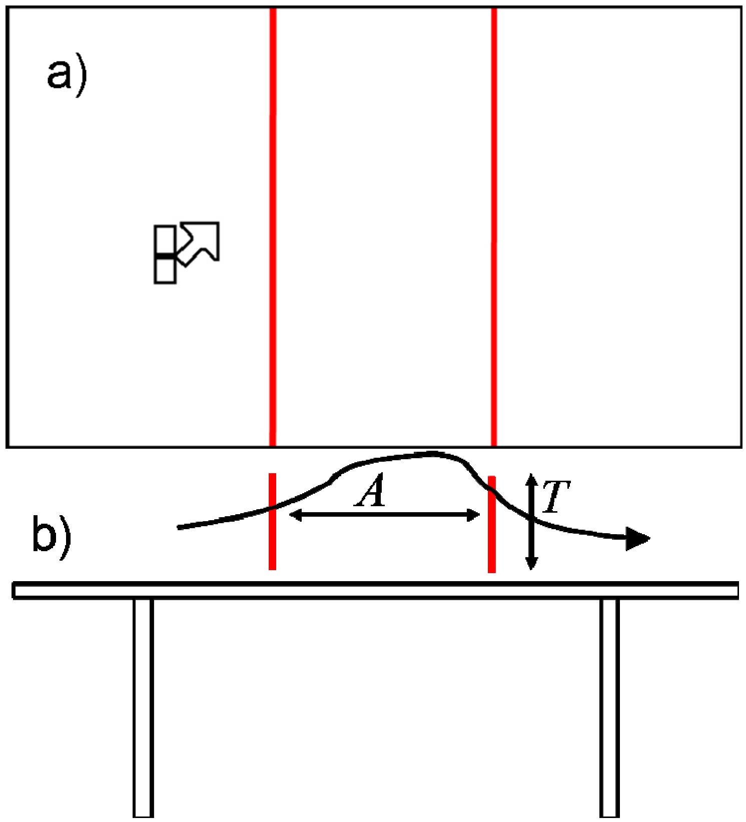

Figure 3.5. The 1D goal crossing task used in Experiment 1. a) Top view b) Front view

To begin a trial, participants had to position the stylus within 10 pixels to the left of the start goal, and above the surface, such that it was within the bounds of the current trial layer. Once this was done, participants had to dwell for 0.6s and then click a button on the stylus. At this point the color of the goals would turn green indicating that the participant could proceed to crossing the goals. These starting constraints were added to control the initial velocity of the pen when the trial began, and to prevent users from going from one trial to the next without regard to accuracy.

When the first goal was crossed it would change color and when the second goal was crossed the trial ended. Both goals had to be successfully crossed from left to right in the correct order for the trial to be completed. An audio cue was given each time a goal was successfully crossed. The position of pen was visualized using cursor. Chapter 4 elaborates on the design and evaluation of the visualization.

Because this was a goal crossing task, the stylus only had to be within the layer bounds when the goals were crossed. If the stylus was not in the layer when the starting goal was crossed, the participant would have to back-track and repeat the crossing for that goal. If this happened with the end goal, the trial would be counted as an error. The total error rate was displayed during the experiment, and participants were told to balance speed and accuracy such that their error rate remained at approximately 4%.

3.3.3 Design

A repeated measures within-participant design was used. The independent variables were layer thickness, *T* (1, 1.5, 2, and 2.5 centimeters), and the distance between the goals, or amplitude, *A* (5, 15, 25, and 35 centimeters). Subjects were treated as random effects. This design resulted in *ID* values ranging from 1.58 to 5.17 as determined by Equation 3.1. A fully crossed design resulted in 16 combinations of *T* and *A*.

The experiment was divided into 4 blocks. Within each block all trials for one thickness were presented before moving on to the next. This was done to prevent confusion of constantly changing layer thicknesses.

Within each block and for each thickness, trials for each of the 4 lengths were presented 9 times in random order, resulting in a total of 576 trials. The ordering of layer thickness was balanced by being reversed for the second participant. Before the first block, a practice session was given, consisting of each of the 16 conditions presented in random order.

3.3.4 Results

Movement time, *MT*, was the main measure for the experiment, defined as the time between crossing the start and end goals. In all experiments we used the mean of movement time for trials of same condition. In order to get a precise measurement of the time when the pen crossed each goal, we linearly interpolated between the last event when the pen was reported to be to the left of the goal, and the first event when the pen was reported to be to the right of the goal. In our analysis of movement time we removed trials in which errors occurred. We also removed outliers more than 3 standard deviations from the group mean movement time (2.5% of the data). In all experiments, we used SAS Software for Windows. Copyright © 2006. SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA.

Repeated measures analysis of variance showed a main effect for *T* ($F_{3,3} = 29$, $p < .0001$) and *A* ($F_{3,3} = 173$, $p < .0001$). Movement times for each thickness were 1.2s for $T = 1$cm, 0.82s for $T = 1.5$cm, 0.81s for $T = 2$cm, and 0.67s for $T = 2.5$. This confirms our belief that movement times will be constrained by the layer thickness.

Figure 3.6 plots the movement times by the index of difficulty, defined by Equation 3.1. Linear regression analysis showed that the data fit to the model with an R^2 value of 0.83. The equation for *MT* is given by:

$$MT = -852 + 503\log_2\left(\frac{A}{T}+1\right) \tag{3.7}$$

The R^2 value is somewhat lower than desired, but it is reasonable to expect that with more participants, the movement times would continue to conform to our model, with a higher fit.

The overall error rate for the experiment was 2.4%, which is slightly lower than the desired 4% error rate. The condition that seemed to have the most effect on error rate was with A=5cm, where the error rate was 7.3%. This gives more explanation as to why our model did not have a higher fit to the data. Indeed if we remove this condition from the data, the R^2 value increases to 0.92.

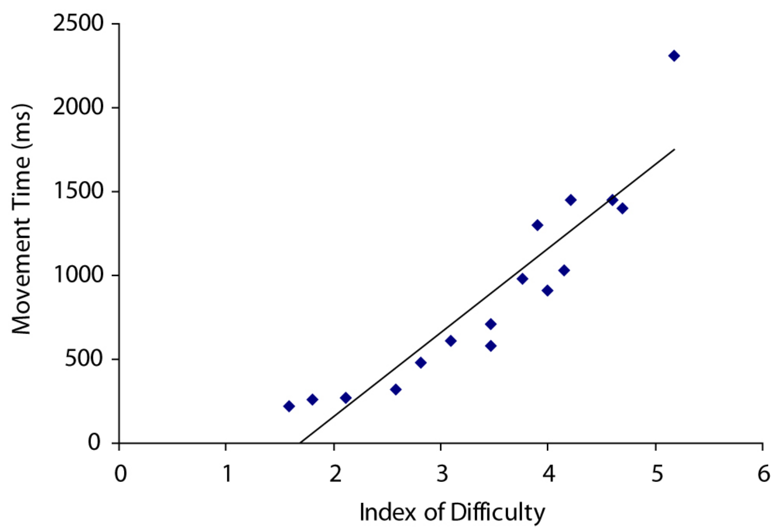

Figure 3.6. Movement times by ID for the 1D goal passing task

Table 3.1. Mean and standard deviation of movement time for goal passing in layers

	Mean	Std. Deviation	N
MT	471.33	352.35	6732

Overall, the data provides the necessary confirmation that a goal crossing task for which the goal is constrained by a layer thickness can be modeled using Fitts' Law. This validates the derivation of our model for a tunneling task that is constrained by a layer thickness (Equation 3.2). We validate this model in the following experiment.

3.4 EXPERIMENT 2: 1D Tunneling

In the previous experiment we found that the layer thickness will affect movement times in a goal crossing task as we would predict from Fitts' Law. While we would expect to see the experimental tasks in actual applications, it was necessary to validate our derivations of the other models which we will be testing in this work.

In this experiment, we focus on the task of steering within an above-the-surface interactive layer, without the presence of directional constraints. An example of such a task is seen when a user must move from one point to another while staying in the tracking state to maintain a mode [12, 31]. Along with investigating human capabilities when performing this task, we will also test the ability of our proposed model (Equation 3.2) to predict movement times.

3.4.1 Participants

Twelve volunteers (8 male, 4 female), aged 21 to 35 participated in the experiment. Participants were right handed and controlled the stylus with the right hand. Four subjects had previous experience with using large digital tables. All participants were tested individually.

3.4.2 Procedure

The general procedure was the same as in the previous experiment. In this case the task was to steer through a layer (tunnel) of thickness T, over a distance A. The task was again accomplished by passing a start and end goal from left to right, however in this case the stylus had to remain within the layer during the entire trial. The tunnel area was depicted as a solid red rectangle, spanning the extent of the display. The left edge of the rectangle was the start goal, and the right edge of the rectangle was the end goal. The goals were again centered with the participants seating position. Figure 3.7 illustrates the task.

The procedure to begin a trial was the same as in Experiment 1. When the trial could begin, the rectangle would turn green, and when the first goal was crossed the tunnel turned orange. As in experiment 1, both goals had to be successfully crossed from left to right in the correct order for the trial to be completed.

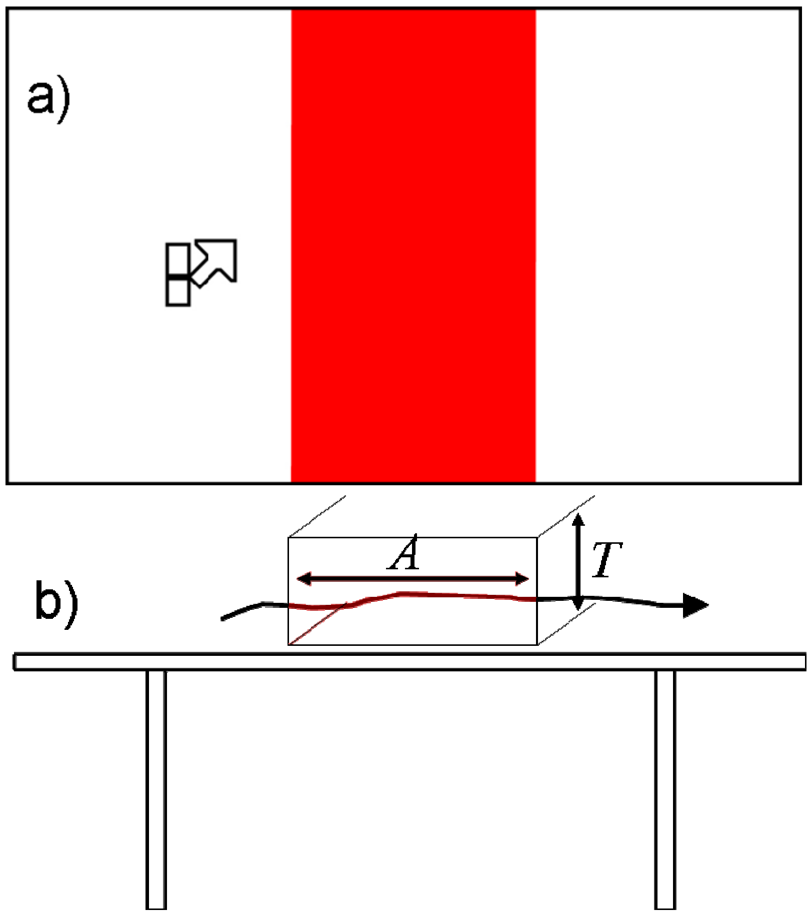

Figure 3.7. The 1D tunneling task used for Experiment 2. a) Top view b) Front view

Because this was now a tunneling task, the stylus had to be within the layer bounds through the entire trial. If the stylus left the layer at any time once the trial began then the trial would be counted as an error.

3.4.3 Design

The design was the same as in Experiment 1. A repeated measures within-participant design was used. The independent variables were layer thickness, *T* (1, 1.5, 2, and 2.5 centimeters), and the distance between the goals, or amplitude, *A* (5, 15, 25, and 35 centimeters). Subjects were treated as random effects. This design resulted in ID values ranging from 2 to 35 as determined by Equation 3.2. A fully crossed design resulted in 16 combinations of *T* and *A*.

The trials within each of the four blocks were again ordered by thickness, with all trials for one thickness being completed before moving on to the next. The ordering of layer thickness was counterbalanced between participants using a 4x4 balanced Latin Square design. Before the first block, a practice session was given, consisting of each of the 16 conditions.

Time Measurement Design

In order to keep the time measurement accurate and more reliable, we used linear interpolation to estimate the precise trial start time and the end time. We recorded the time, just before a trial began and as well as just after the trial started. Then the time is calculated as follows:

$$T = \frac{W_1 T_b + W_2 T_a}{W_1 + W_2}, W_1 = \frac{x - x_b}{x_a - x_b}, W_2 = \frac{x_a - x}{x_a - x_b} \qquad (3.8)$$

where W_1 and W_2 are weights. x_a and x_b are abscissa when the times T_a and T_b are recorded before and after a trial has begun. x is the abscissa of the start of the tunnel. We repeated the same method to estimate the end time as well.

3.4.4 Results

Movement time, *MT*, was again the main dependent measure and had the same definition as in Experiment 1. We again removed trials in which errors occurred, as well as outliers which were more than 3 standard deviations from the group mean movement time, 1.6% of the data.

Repeated measures analysis of variance showed a main effect for *T* ($F_{3,33} = 243$, $p < .0001$) and *A* ($F_{3,33} = 2477$, $p < .0001$), and a significant *T*x*A* interaction ($F_{9,99} = 39.7$, $p < .0001$). Mean movement times for each thickness were 0.61 for *T* = 1cm, 0.48s for *T* = 1.5cm, 0.42s for *T* = 2cm, and 0.41s for *T* = 2.5. Post hoc analysis shows that all pairs of thickness are significantly different except for *T* = 2cm and *T* = 2.5cm. Figure 3.8 illustrates the interaction between *T* and *A*. It can be seen that the effect of *T* becomes stronger for higher values of *A*. Even so, there is little difference between *T* = 2 and *T* = 2.5 even for the largest distance. This suggests that the layer of thickness within 2 to 2.5cm can be used for design, when the steering distance is less than 35 cm.

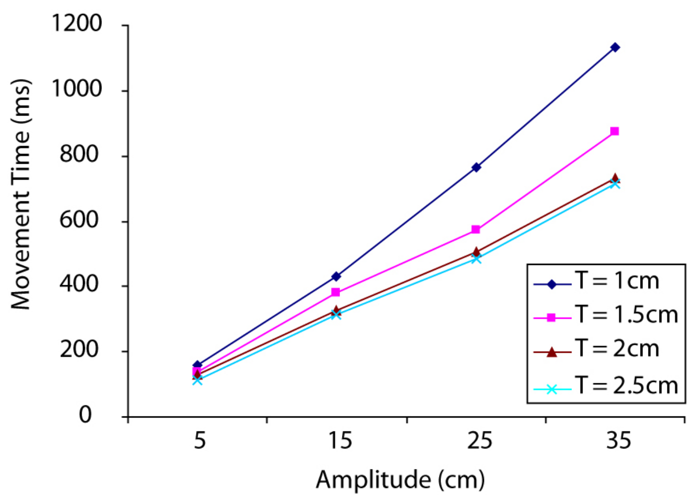

Figure 3.8. Movement times by amplitude and layer thickness

Figure 3.9 plots the movement times by the index of difficulty, defined by Equation 3.2. Linear regression analysis showed that the data fit to the model with an R^2 value of 0.92. The movement time *MT*, is given by the equation:

$$MT = 84.7 + 31.25\left(\frac{A}{T}\right) \qquad (3.9)$$

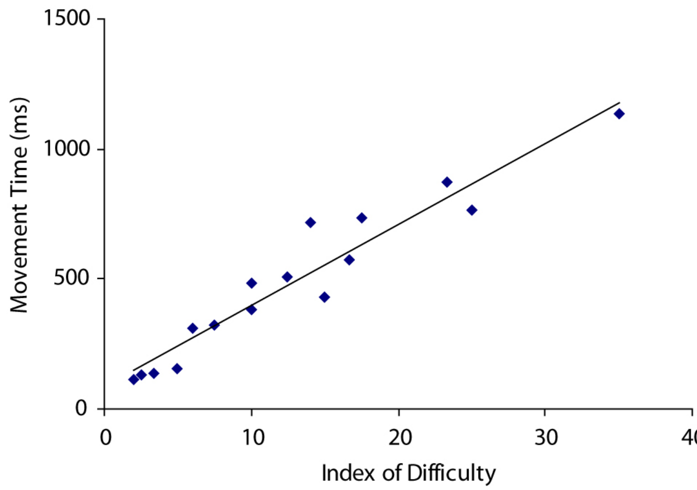

Figure 3.9. Movement times by ID for the 1D steering task

Table 3.2. Mean and standard deviation of movement time for 1D tunneling in layers

	Minimum	Maximum	Mean	Std. Deviation
MT	19.00	1882.00	471.33	352.35
Thickness	1.00	2.50	1.75	0.55
Length	5.0	35.0	19.89	11.15

The overall error rate for the experiment was only 1%. While this is lower than the desired 4% level, it does indicate that our experimental setup allows participants to navigate within the layer boundaries. Error rates were slightly higher for larger values of *A* and smaller values of *T*, but remained under 3% across all conditions except for *A* = 35cm, *T* = 1cm, for which the error rate was 8.1%.

The results of Experiments 1 and 2 have provided useful information about navigating within above-the-surface interaction layers when the only constraint is the thickness of the layer. In the following experiments we investigate what happens when there are also directional constraints imposed on the movements.

3.5 EXPERIMENT 3: A Pilot Study of 2D Goal Passing

In the previous sections we have investigated a tunneling task when movements are constrained by the layer thickness. We validated that our model, which is based on Accot and Zhai's steering law [1], can be used to predict movement times. We now turn our focus to the task of navigating within a layer along a path which imposes a directional constraint. Such a task is seen in previously developed interaction techniques, such as Hover Widgets, where users make specific gestures defined by tunnel boundaries in the tracking state of a pen based system [28].

Before investigating this specific task, we will first look at the constrained version of the goal crossing task which was used in Experiment 1. It is again imperative to do this as the model for this task is used to derive the model for the tunneling task. In validating our proposed model for the constrained goal crossing task, we will also be validating our derivation of the model proposed for the more practical constrained tunneling task. As with Experiment 1, this task is theoretical in nature, so we again only ran two participants through the experiment (Figure 3.10).

3.5.1 Participants

Two volunteers (both males) aged 19 participated in the experiment. Both participants were right handed and controlled the stylus with the right hand. Neither of the subjects had previous experience with using large digital tables. However, both of them had used a Tablet PC before. Both subjects were tested individually.

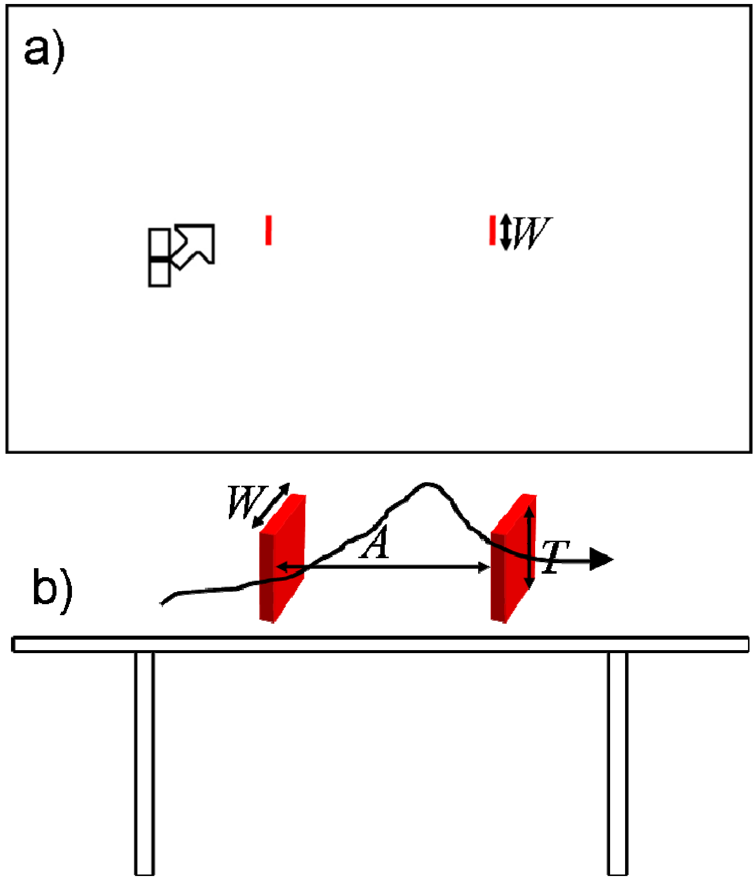

Figure 3.10. The 2D goal passing task used for Experiment 3. a) Top view b) Front view

3.5.2 Procedure

The general procedure for this experiment was the same as in Experiment 1. However, in this case the goals had a finite width, *W*, as they were used to impose the directional constraint. Figure 3.10 illustrates the task. As with Experiment 1, users had to successfully cross both goals from left to right to complete the task. However, in this experiment, a successful cross required the pen to be within the layer bounds, and within the extents of the goal. As with the previous experiments, if the cross was unsuccessful, then the participant would have to back-track and repeat the crossing for that goal.

3.5.3 Design

A repeated measures within-participant design was used. The independent variables were layer thickness, *T* (1, 1.5, 2, and 2.5 centimeters), goal width, *W* (1, 1.5, 2, and 2.5 centimeters), and the distance between the goals, or amplitude, *A* (5, 15, 25, and 35 centimeters). Subjects were treated as random effects. The resulting range of *ID* values, as calculated by Equation 3.3, will depend on the value of η, which will be determined by the results obtained in this experiment. A fully crossed design resulted in 64 combinations of *T, A* and W.

The experiment was divided into 3 blocks. Within each block trials were ordered by thickness. Within each block and for each thickness, trials for each of the 16 *W* and *A* combinations were presented 5 times in random order, resulting in a total of 960 trials. The ordering of layer thickness was balanced by being reversed for the second participant. Before the first block, a short practice session was given.

3.5.4 Results

Movement time, *MT*, was again the main dependent measure, and we removed trials in which errors occurred, as well as outliers which were more than 3 standard deviations from the group mean movement time, 0.86% of the data. The overall error rate for the experiment was 3.3%, with higher error rates for smaller values of *T* and *W* and larger values of *A*.

Repeated measures analysis of variance showed a main effect for *T* ($F_{3,3} = 2.7$, $p < .05$), *W* ($F_{3,3} = 294$, $p < .0001$) and *A* ($F_{3,3} = 1380$, $p < .0001$). The weaker significance for *T* indicates that the layer thickness may not have as much impact when a task is also constrained by tunnel width. Movement times for the four values of *T* were between 0.61s and 0.65s, while they ranged from 0.19s to 1.1s for the values of *A* and 0.48s to 0.87s for the values of *W*.

By least-squares fit method, we estimated the value of η for our model in Equation 3.3 to be 0.002. This indicates that the impact of *T* is almost negligible in comparison to the effect of *W*. Using this value of η, linear regression analysis gives an R^2 value of 0.88. Because of the low value of η, if we ignore thickness constraint, Equation 3.3 reduces to a naïve model which only considers *A* and *W*:

$$ID = \log_2\left(\frac{A}{W}+1\right) \qquad (3.10)$$

The results of linear regression analysis are illustrated in Figure 3.11. The movement time *MT*, is given by the equation:

$$MT = -604.4 + 340\log_2\left(\sqrt{\left(\frac{A}{W}\right)^2 + 0.002\left(\frac{A}{T}\right)^2} + 1\right) \qquad (3.11)$$

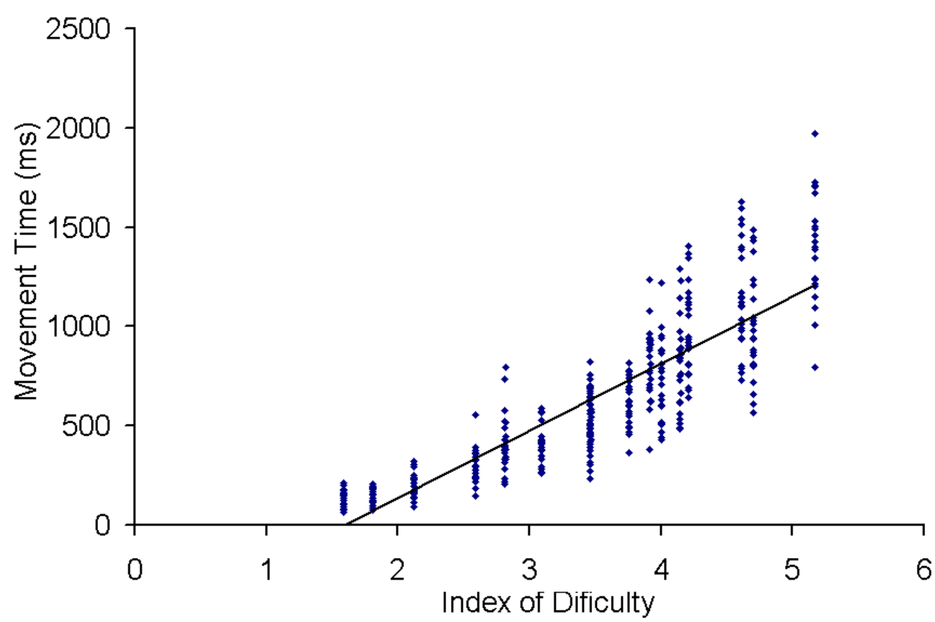

Figure 3.11. Movement times by ID for the 2D goal passing task

Table 3.3. Mean and standard deviation of movement time for 2D goal passing in layers

	Minimum	Maximum	Mean	Std. Deviation
Length	5.0	35.0	19.76	11.19
Width	1.00	2.50	1.76	0.55
MT	24.00	2109.00	615.62	410.66
Thickness	1.00	2.50	1.75	0.55

This result indicates that during the goal crossing task, it is much easier to control the height of the pen above the display surface, in comparison to staying within a directional constraint. We should take into account that this was only a 2-participant experiment, and in the next experiment we will revisit the issue. However, the result does tell us that for the 2D tunneling task, which will be presented in the next experiment, in addition to testing the model presented in Equation 3.6, we should also consider the naive model which ignores the layer thickness:

$$ID = \frac{A}{W} \qquad (3.12)$$

3.6 EXPERIMENT 4: 2D Tunneling

In this experiment, we investigate the 2D tunneling task, where the user must navigate through an above-the-surface layer, while following a specific path that imposes a directional constraint. As with the Experiment 2 task, this is an important task to understand, as it is an element of existing interaction techniques [23]. We hope to gain an understanding of how the layer thickness, T, and tunnel width, W, affect movement time, and how these effects compare to one another (Figure 3.12). The results of Experiment 3 indicate that W will be the dominantly constraining variable. We will also test the validity of our originally proposed model for this task (Equation 3.6), along with the naïve form of this model (Equation 3.12), proposed based on our results of Experiment 3.

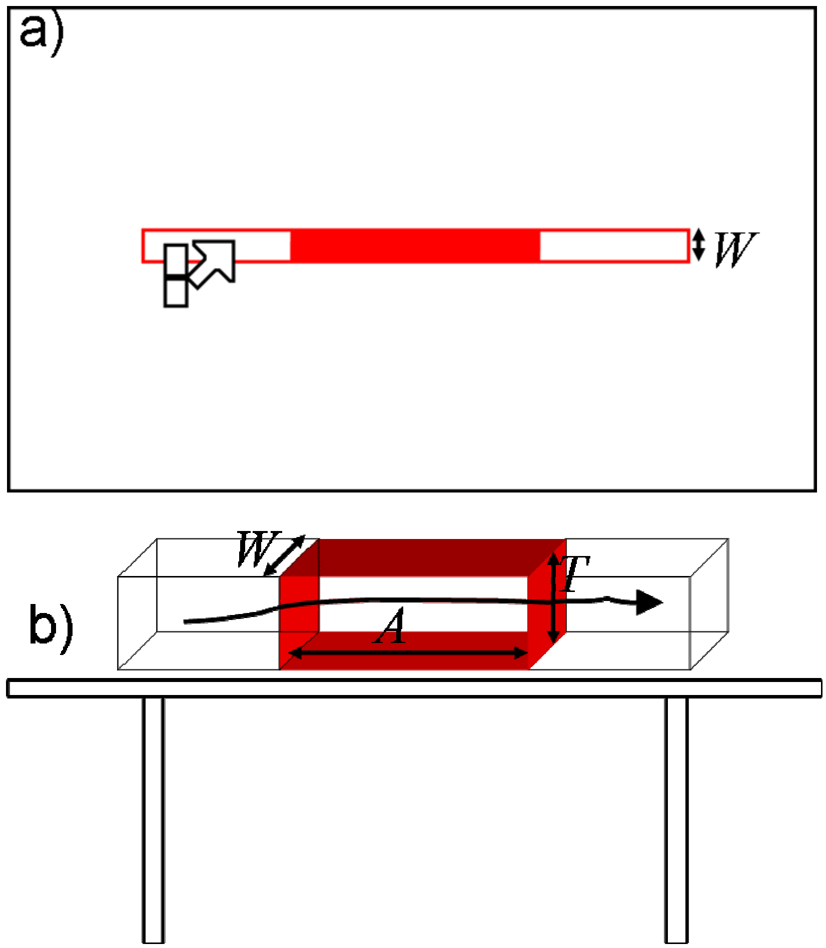

Figure 3.12. The 2D tunneling task used for Experiment 4. a) Top view b) Front view

3.6.1 Participants

Twelve volunteers (10 male, 2 female), aged 21 to 35 participated in the experiment. Participants were right handed and controlled the stylus with the right hand. Four subjects had previous experience with using large digital tables, and 3 of them had used a Tablet PC before. All participants were tested individually.

3.6.2 Procedure

The general procedure for this experiment was the same as in Experiment 2. However, in this case the tunnel had a finite width, *W*, imposing a directional constraint on the user's movement.

For extra visual feedback, the starting area was rendered on both sides of the tunnel as rectangles. Figure 3.12 illustrates the task. Users had to successfully cross both goals from left to right, while staying within the bounds of the layer and tunnel. If a goal cross was unsuccessful, the participant would have to back-track and repeat the crossing for that goal. The trial was counted as an error if at any time during the trial pen exited the bounds of the layer, or the width of the tunnel.

3.6.3 Design

The design was the same as in Experiment 3. A repeated measures within-participant design was used. The independent variables were layer thickness, *T* (1, 1.5, 2, and 2.5 centimeters), goal width, *W* (1, 1.5, 2, and 2.5 centimeters), and the distance between the goals, or amplitude, *A* (5, 15, 25, and 35 centimeters). Subjects were treated as random effects. The resulting range of *ID* values, as calculated by our originally proposed model (Equation 3.6), will depend on the value of η, which will be determined in this experiment.

The trials in each of the three blocks were again ordered by thickness. Within each block and for each thickness, trials for each of the 16 *W* and *A* combinations were presented 5 times in random order, resulting in a total of 960 trials. The ordering of layer thickness was counterbalanced between participants using a 4x4 balanced Latin Square design. Before the first block, a practice session was given, consisting of 16 random trials.

3.6.4 Results

Movement time, *MT*, was again the main dependent measure, and we removed trials in which errors occurred, as well as outliers which were more than 3 standard deviations from the group mean movement time, 1.29% of the data. The overall error rate for the experiment was 2.6%, and as with the previous experiment higher error rates resulted from smaller values of *T* and *W* and larger values of *A*.

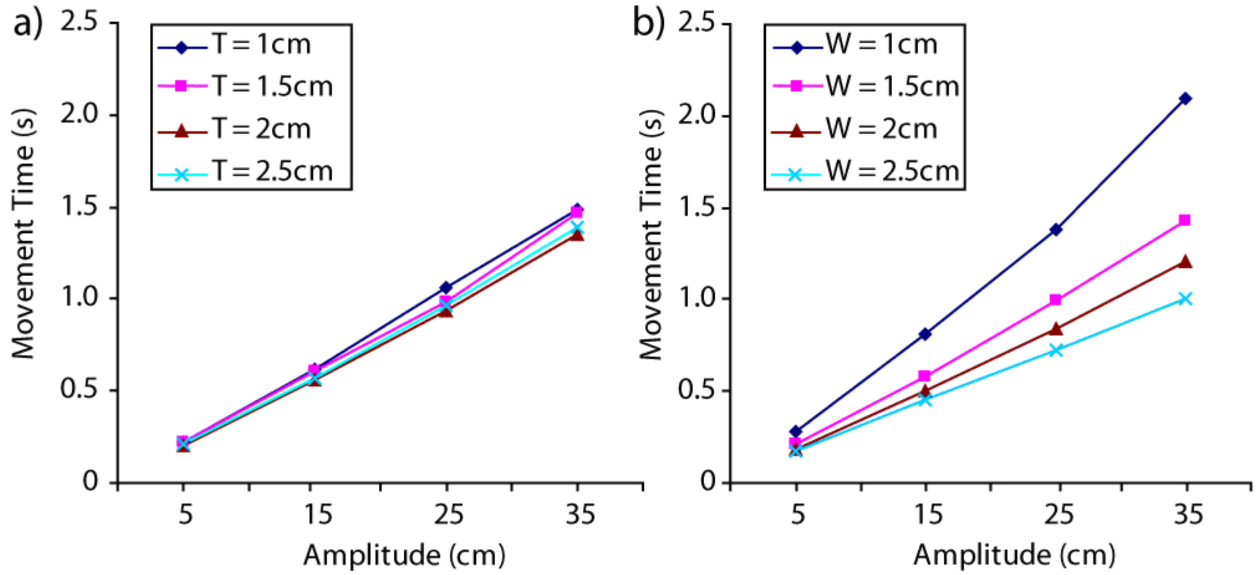

Figure 3.13. Interaction effects observed in Experiment 4. a) *T*x*A* interaction. b) *W*x*A* interaction

Repeated measures analysis of variance showed a main effect for *T* ($F_{3,33} = 35.2$, $p < .0001$), *W* ($F_{3,33} = 1366$, $p < .0001$) and *A* ($F_{3,33} = 6544$, $p < .0001$). We also found significant *A*x*T* ($F_{9,99} = 4.48$, $p < .0001$) and *A*x*W* ($F_{9,99} = 199$, $p < .0001$) interaction effects on *MT*. These effects are illustrated in Figure 3.13. It can be seen that the effect of both *T* and *W* become stronger when *A* is increased. However, by comparing the two figures we again see that the effect of *W* on *MT* is much stronger than *T*, especially for when *A* is greater than 5cm. Overall movement times for the four values of *T* were all between 0.75s and 0.84s, while they ranged from 0.21s to 1.4s for the four values of *A* and 0.59s to 1.1s for the four values of *W*. It is also interesting to compare Figure 3.13a to Figure 3.7 from Experiment 2. We see that the presence of the directional constraint in this task drastically reduces the effects of *T*.

By a least-squares fit method, we estimated η for our model in Equation 3.6 to be 0.1638. This is larger than its value for the goal crossing task discussed in the previous experiment, indicating that our Euclidian model may be more appropriate for this task. Using this value, linear regression analysis gives a high R^2 value of 0.989 (Figure 3.14). The movement time, *MT* is given by the equation:

$$MT = 20.59 + 55.85\sqrt{0.16\left(\frac{A}{T}\right)^2 + \left(\frac{A}{W}\right)^2} \qquad (3.13)$$

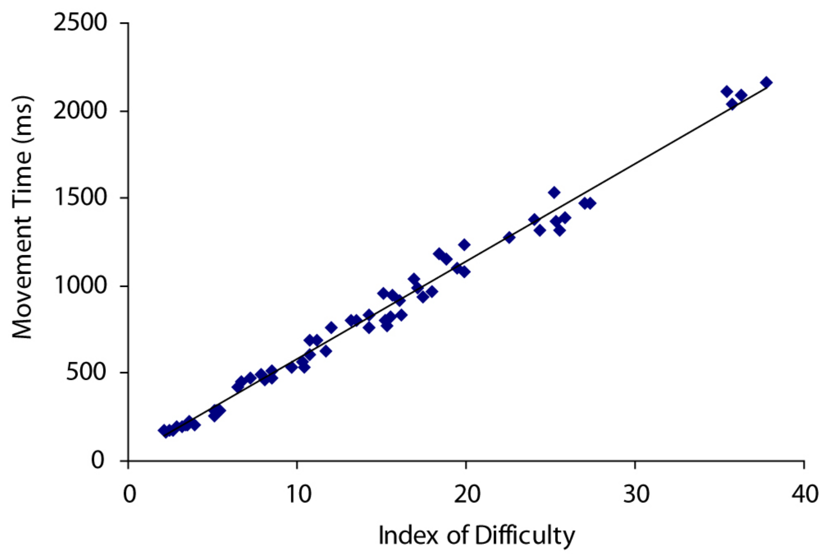

Figure 3.14. Movement time by ID for the 2D steering task

Table 3.4. Mean and standard deviation of movement time for 2D tunneling in layers

	Minimum	Maximum	Mean	Std. Deviation
Thickness	1	3	1.75	0.55
Length	5	35	20.00	11.18
Width	1	3	1.75	0.55
MT	31.00	6015.00	810.07	638.21

We also tested the naïve model (Equation 3.12), proposed based on the results of Experiment-3. It also performed well, with slightly lower R^2 value of 0.97. Even though the Euclidian model provides a higher R^2 value, it is again interesting that the naïve model provides such a high fit. This may in part be due to the fact that participants were able to rest their hand on the display surface, which helps them physically constrain the stylus height. However, we must recall that in Experiment 2, *T* had a much stronger effect, with the same values being tested, so we have not just chosen values of *T* which were too "easy". We have demonstrated that in the presence of a directional constraint, layer thickness has much less of an effect on movement time.

3.7 3D Steering Model

The experiments described above confirm the validity of the 2D steering model. Based on this model we derive a final model for steering in above-the-surface layers positioned at different heights above the display [13, 36]. We define the *Height* H as the distance between the bottom plane of the layer and the display surface (Figure 3.15). We know that steering in a layer constrained by the layer thickness is given by:

$$MT = a + b\left(\frac{A}{T}\right). \tag{3.14}$$

We have shown that 2D goal passing can be modeled by the Euclidian model for bivariate pointing (Equation 2.2) [18] given by:

$$MT = a + b\log_2\left(\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{T}\right)^2} + 1\right). \tag{3.15}$$

2D goal passing can be described as crossing two goals of width W and thickness T placed perpendicular to the display surface. The goals are separated by a distance A (Figure 3.16). From

Equation 2.4 we can infer that if we neglect orientation we can extend the bivariate model. By analogy we assume that the variable H is related as given by:

$$MT = a + b\log_2\left(\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{T}\right)^2 + \beta\left(\frac{A}{H}\right)^2} + 1\right). \qquad (3.16)$$

We employ the goal passing methodology used by Accot and Zhai[1] again. We break the tunneling task constrained by height into a series of *N* goal crossing tasks (Figure 3.16). By adding the IDs for each of the N tasks, where each goal is separated by a distance *A\N*, we get:

$$ID_N = N\log_2\left(\sqrt{\left(\frac{A}{NW}\right)^2 + \eta\left(\frac{A}{NT}\right)^2 + \beta\left(\frac{A}{NH}\right)^2} + 1\right) \qquad (3.17)$$

We can see that as *N* approaches infinity, the task converts into above-the-surface steering. To obtain ID for the steering task we take limits ID_N as N tends to infinity. Using a first order Taylor series expansion of $log_2 (1 + x)$, we obtain:

$$ID = \lim(N \to \infty) ID_N = \frac{1}{\ln(2)}\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{T}\right)^2 + \beta\left(\frac{A}{H}\right)^2} \qquad (3.18)$$

By omitting 1\ln (2) for simplicity we arrive at the model shown below:

$$MT = a + b\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{T}\right)^2 + \beta\left(\frac{A}{H}\right)^2} \qquad (3.19)$$

In the sections that follow we describe experiments, where we analyze motor performance when steering in layers above the surface. We examine the validity of the models based on the results of the experiments.

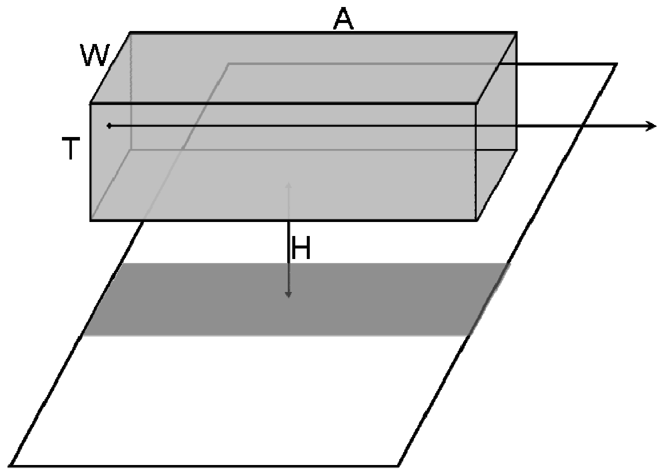

Figure 3.15. Steering through a tunnel, constrained by the layer thickness, *T*. width *W* and height *H*

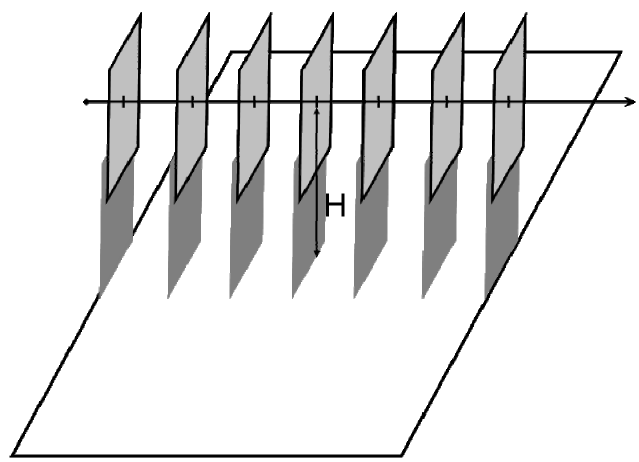

Figure 3.16. A series of goal crossing tasks at height *H*

3.8 EXPERIMENT 5: 3D Steering

In this experiment, we study 3D steering, where the users steer through a layer above the surface positioned at different heights. Users follow a path that imposes a directional constraint along with the height and thickness constraints. These types of tasks are common in multilayer interaction techniques [59]. We investigate these tasks to understand how the layer thickness, *T*, tunnel width, *W*, and height *H* affect movement time. We will also see how these independent variables interact with each other. We will use the results to validate the model that we have proposed (Equation 3.19).

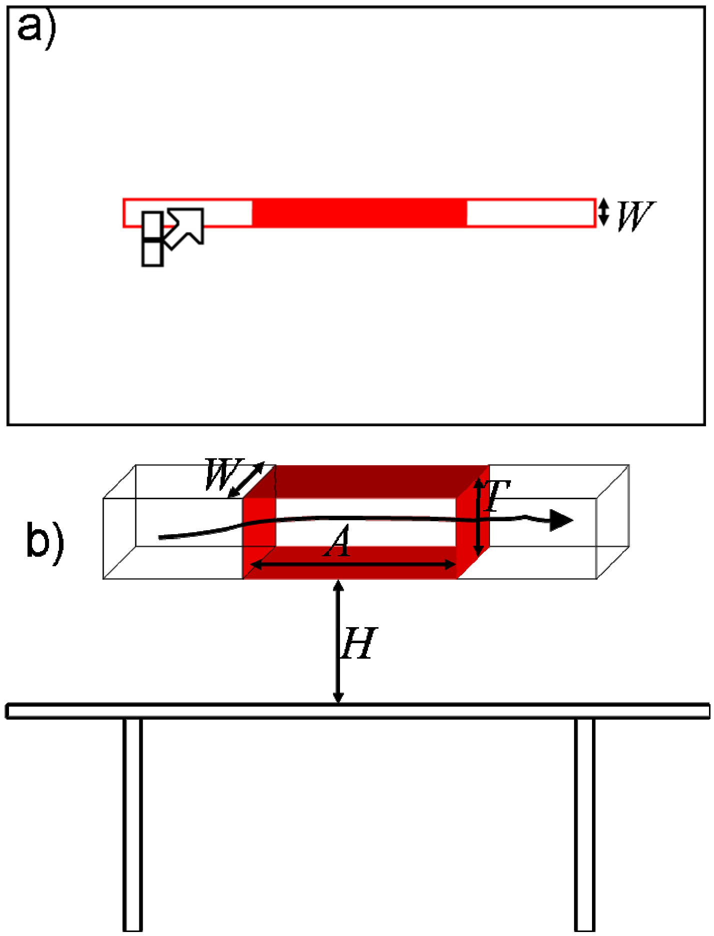

Figure 3.17. The 3D steering task used in the experiment. a) Top view b) Front view

3.7.1 Participants

Eight volunteers (7 male, 1 female), aged 25 to 35 participated in the experiment. Participants were right handed and controlled the stylus with their right hand. Four subjects had previous experience with using large digital tables, and rest of them were first time users. All participants were tested individually. Their wrist length varied between 17.7cms to 20.3cms and their forearm length varied between 41.9cms to 50.8cms. The wrist and forearm length were defined as the distance between tip of middle finger to wrist bone and the distance between tip of middle finger to forearm bone (radius and ulna).

3.7.2 Procedure

The task was accomplished by steering through a tunnel of width W , thickness T, and a length of A, positioned at a height H (Figure 3.17). A trial began when the participants positioned the stylus beyond 10 pixels to the left of the start of the tunnel, and at an appropriate height, such that it was within the bounds of the current trial layer. Initially the tunnel was colored red. After positioning the stylus, participants had to click the button on the stylus. This turned the tunnel to a green color indicating that the participant could proceed steering through the tunnel. A dwell space of 10 pixels before the tunnel was provided to stop accidental crossings. This was done to control the initial velocity of the pen when the trial began. This also prevented the users going from one trial to the next without regard to constraints and accuracy.

When the stylus entered the tunnel, it turned yellow to indicate that the trial had started and was in progress. The trial ended when the stylus reached the other end of the tunnel. The tunnel turned red again to indicate that the trial was over. An audio cue was given each time a task started and also when the task ended.

The experiment was designed to present next trial after 0.6s when a trial ended, to stop ballistic movements from the user. If the user started the steering outside the starting point of the tunnel, the trial would not start. The user had to back-track and start the task again, being within the bounds of the tunnel. If the stylus left the bounds of the tunnel at any place when the trial was running, it would be counted as an error. The total error rate was displayed during the experiment, and participants were told to balance speed and accuracy such that their error rate remained at approximately 4%.

Audio cues were given when the height of the tunnel changed. Thickness and height of the tunnel were indicated using a bar next to the tunnel (Figure 3.17).

3.7.3 Design

A repeated measures within-participant design was used. The independent variables were layer thickness, *T* (1.5, 2.5, and 3.5 centimeters), the distance between the goals, or amplitude, *A* (5, and 25, centimeters), the width W (1.5 and 2.5 centimeters) and height H (5, 15 and 25 centimeters). Subjects were treated as random effects. The *ID* values are dependent on the η and β that will be estimated based on the results of the experiment. A fully crossed design resulted in 24 combinations of *W*, *H, A* and *T*.

The experiment was divided into 2 blocks. The trials in each block were ordered by thickness, with all trials for one thickness being completed before moving on to the next. This was done to prevent confusion of constantly changing layer thicknesses.

Within each block and for each thickness, trials for each of the 4 lengths were presented 5 times in random order, resulting in a total of 360 trials. The ordering of layer thickness was counterbalanced between participants using a 4x4 balanced Latin Square design. Before the first block, a practice session was given, consisting of each of the 16 conditions presented in random order.

3.7.4 Results

We measured movement time for each of the trials in the experiment. MT was defined as the time between entering the tunnel and leaving the tunnel. To get the precise measurement of time, we linearly interpolated between the events before and after entering the tunnel. This was repeated also while ending the steering trial. Trials with errors were not considered for analysis.

Outliers, more than 4 standard deviations from the group mean MT, were removed and they constituted 4.5% of the data. By considering data within 4 standard deviations from the group mean prevents the excluding meaningful data points allowing us to consider more variation caused by *H* variable. In the experiments that follow analysis of data was carried out using SPSS Software, Version 14.0 for Windows. Copyright © 1989-2005 SPSS Inc. SPSS and all other SPSS Inc. product or service names are registered trademarks or trademarks of SPSS Inc., Chicago, Illinois, USA. The SPSS repeated measures ANOVA accounts for sphericity of data by applying the Geisser-Greenhouse correction. Geisser-Greenhouse corrects for the equality of variance ensuring the sphericity.

Repeated measures analysis of variance (full factorial model) showed a main effect for *H* ($F_{2, 14} = 19.86$, $p < 0.0001$), *T* ($F_{2, 14} = 77.00$, $p < 0.0001$), *W* ($F_{1, 7} = 20.94$, $p < 0.003$), and *A* ($F_{1, 7} = 70.59$, $p < 0.0001$). The effects of *H, T, W* and *A* on *MT* were statistically significant. We also found significant *A*x*T* ($F_{2,14} = 33.81$, $p < 0.0001$), *A*x*H* ($F_{2,14} = 24.21$, $p < 0.0001$) and *T*x*H* ($F_{4,28} = 6.91$, $p < 0.001$) interaction effects on *MT*. However, interaction effects of *W*x*H* ($F_{2,14} = 0.48$, $p < 0.630$) and *T*x*W* ($F_{2,14} = 0.414$, $p < 0.67$) on *MT* were not significant. Post-hoc analysis with Games-Howell criterion reveals that there is no significant difference between *MT* for layer thickness 2.5 cm and 3.5 cm while the difference between *MT* for other layer thicknesses is significant. The difference between *MT* for all heights is significant. (The sample size for each condition was restricted to 5, to remove the effect of fatigue on the trials.) Mean movement times for each height were 1.325s for *H* = 5cm, 1.695s for *H* = 15cm, 2.012s for *H* = 25cm. We can see that movement times will be constrained by the height of the layer above the surface.

Figure 3.18 plots the movement times by the index of difficulty, defined by Equation 3.19. Figure 3.19 depicts movement time for thickness and height combinations. Linear regression analysis showed that the data fit to the model with an R^2 value of 0.86. The equation for *MT* is given by:

$$MT = 0.0052 + 01.85\sqrt{\left(\frac{A}{W}\right)^2 + 1\left(\frac{A}{T}\right)^2 + 1\left(\frac{A}{H}\right)^2} \qquad (3.20)$$

The R^2 value is lower than usual value for a good fit, but we believe that by increasing sample size the movement times would continue to conform to our model, with a higher fit.

Table 3.5. Mean and standard deviation of movement time for steering in layers at different heights

	N	Minimum	Maximum	Mean	Std. Deviation
Thickness	2613	1.5	3.5	2.523345	0.809963
Height	2613	5	15	9.875622	4.082541
MT	2613	23	11562	1669.196	1642.908

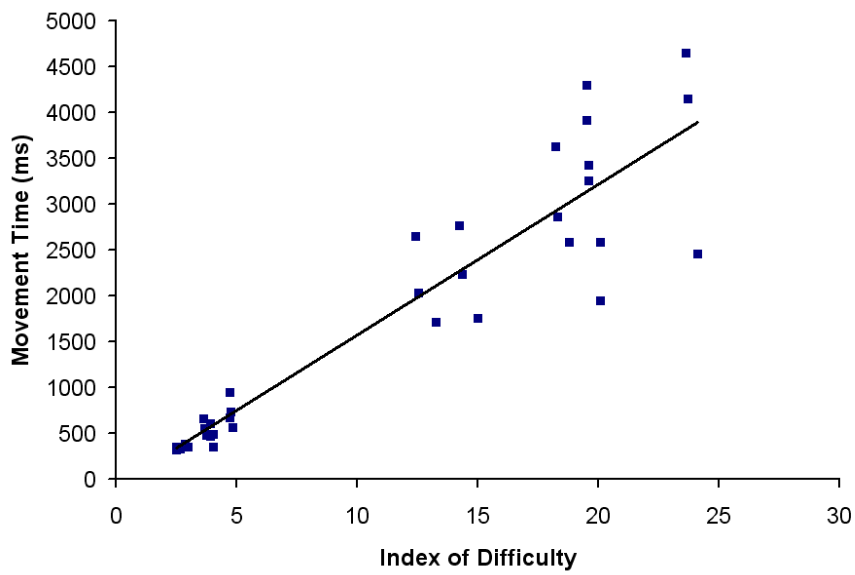

Figure 3.18. Movement times by ID for the 3D Steering task

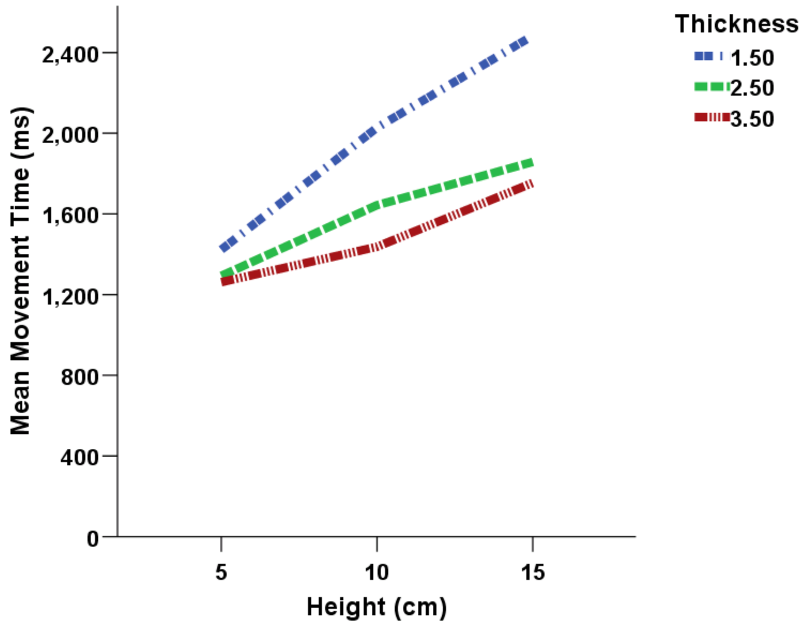

Figure 3.19. Movement times by Height for the 3D Steering task

CHAPTER 4

LAYER VISUALIZATION

This chapter discusses the visualization designs and experiment conducted to evaluate the designs for above-the-surface interaction. The chapter begins with a description of a single layer visualization design used to evaluate the models. Next, several multilayer visualizations designed from the perspective of the information visualization will be discussed. Finally an experimental evaluation of the visualization designs is presented.

For users to be able to efficiently navigate through an above-the-surface interaction layer, they must be aware of the position of their stylus within the layer, as well as the thickness of the layer. This is especially important for our experimental procedure, as the layer thickness is an independent variable, and thus changes from one trial to the next. We use a cursor visualization to provide this information to the user, similar to the way that pressure widgets can be used to convey pressure information [53]. Through informal usage observations and iterative design we converged on the following basic visualization approach.

4.1 Basic Visualization Design

Basic visualization design consists of a 5x20 pixel rectangle, with the top and bottom of this rectangle representing the top and bottom boundaries of the current layer. Within this rectangle, a small 5 pixel horizontal line extends from the base of the cursor to the right (Figure 4.a). This line represents the current height of the input device within the layer. The position never changes in relation to the position of the cursor. It is the position of the rectangle that changes with the height of the stylus, such that the position of the line relative to the rectangle always indicates the position of the stylus in relation to the top and bottom boundaries of the layer. Therefore, moving the pen down will move the rectangle upwards (Figure 4.b), and moving the pen up will move the rectangle downwards (Figure 4.d). If the cursor leaves the lower or upper bounds of the layer, then the rectangle will jump to be above or below the line accordingly (Figure 4.c, e), and the rectangle will be filled red. This was done because in our experiment, an error state is entered if the stylus leaves the layer. Outside of our experimental paradigm, other design approaches could be investigated, especially if multiple layers exist that the stylus could move between, such as in the work by Subramanian et al. [59].

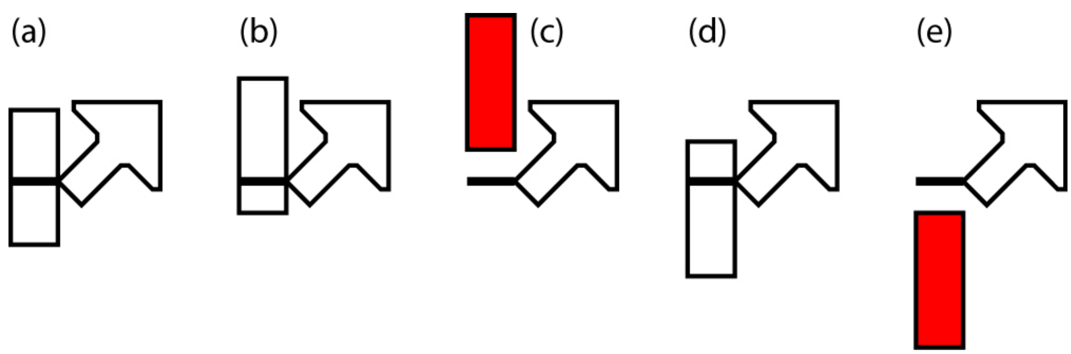

Figure 4.1. Cursor visualization

We used the basic visualization design in the all the experiments described in the Chapter 3. Users comfortably used the visualization to perform steering tasks. However, the basic design visualizes only one above-the-surface layer. To understand how well can this design be extend to multilayer above-the-surface interaction, we considered many visualization designs for multilayer above-the-surface interactions and evaluated them through user experiments. The section below details the design and evaluation of these designs.

4.2 Exploratory Study: Testing Variations on the Basic Design

Visualizations coupled to cursors can embody large numbers of variables while letting the users focus on the task without having to switch attention [25]. The objective here is to design cursors coupled with a widget to visualize the multilayer input space. Using this, users should be able to know and control the position of the stylus above the display surface as well as within the layer. The first task is to arrive at an efficient information structure for visualization [64, 34]. Using this information structure, we have to design cursors types to visualize above-the-surface layers which include the elements *CD ratio*, *overview and detail*, and *layer thickness*, to study their effects.

There were several design options based on previous research into Structural Information Theory (SIT) (See Section 2.4.2) and results of the pilot studies. All these designs had to consider two necessary elements: a widget to indicate the stylus position above the display and a traditional hotspot to facilitate pointing and selection. We considered three designs: Bull's eye design, Arrow design, and Grid design. (See Figure 1.2). We designed an image selection application that used these designs. Two users used the application for ten minutes. Subjective feedback from the users and observations suggested that the designs based on a rectangular grid are preferable. This is also supported by the previous studies [53, 36] arguing that grid mapping is more intuitive for controlling discrete levels. This may be because a grid is likely to be interpreted as a side view of multiple layers. From SIT (See Section 2.4.2) we know that the visual system prefers the simplest interpretation of the visual stimuli [34]. Previous studies have also emphasized visual separation of the visualization widget and pointing hotspot [36]. Based on these three perspectives we chose the rectangular grid design for the visualization element and a traditional arrow for pointing.

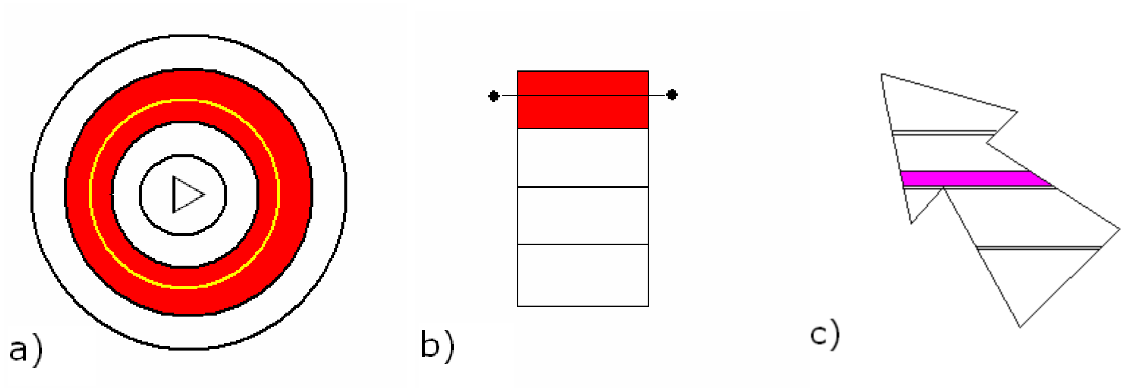

Figure 4.2. a) Bull's Eye cursor b) Grid cursor c) Arrow cursor

4.3 A Study of the Layer Visualization Designs

In this section, the general structure of the visualization design using a cursor is outlined, four visualization designs based on the structure are presented resulting in four types of cursors and the designs are evaluated through a user study, and the outcome and implications of the study are discussed.

The visualization designs consist of an arrow which we call the *pointing element* and a rectangular grid which we call the *layer element*. The layer element is a rectangle formed by smaller rectangles. Each small rectangle represents a layer. We designed layers with four such rectangles representing four layers above the display. A horizontal line represents the position of the stylus above the active surface of the display as well as the position within the layer. The bottom and top of the each rectangle represents the bottom and top of the layer.

The pointing element of the cursor is an arrow as in a traditional desktop cursor, with the tip of the arrow being the hotspot. The hotspot of the cursor always remained directly below the stylus. The bottom edge of the arrow was attached to the layer element next to the horizontal line indicating the stylus position. The pointing element was always tied to the x-y position of the stylus. The layer element moved up and down indicating the position of the stylus in the layer above the display.

Design factors such as *CD ratio*, *overview and details* were embedded in the cursor designs to obtain four variations on the general structure. The variations in the cursor design are depicted in Figure 4.3. In all the visualizations, only the layer element differs; the pointing element remains the same.

4.3.1 Cursor Designs

Overview Cursor (OV)

In this cursor, the layer element is a rectangular grid. The height of the small rectangles corresponding to the layers does not change when the thickness of the layers is changed. Instead the CD ratio changes when the thickness of layers changes. The visualization provides an overview but the details of the layer under use were not shown (see Figure 4.3a).

Overview with Direct Mapping Cursor (ODM)

This is a combination of the overview layer element with the direct mapped layer element. There are two rectangles in the layer element; one provides focus and the other provides an overview (Figure 4.3b). The overview portion of the layer element has a CD ratio relative to thickness while the focus portion has a CD ratio without gain.

Partial Overview Cursor (PO)

In this visualization design, the rectangle representing the layer under use is enlarged (see Figure 4.3c) to cover the most of the area of the layer element. The remaining layers are represented by small rectangles. While the design shows details of the layer under use, the overview of the layers shrinks, reducing the full overview.

Direct Mapped Cursor (DM)

In this cursor, the layer element is a rectangular grid with a height of the smaller rectangles equal to the thickness of the layers. Each rectangle represents a layer and the horizontal line indicates the position of the stylus in the layer. The control is mapped to display without gain. Thus, as the thickness of the layer varied, the height of the rectangles also varied (Figure 4.3d).

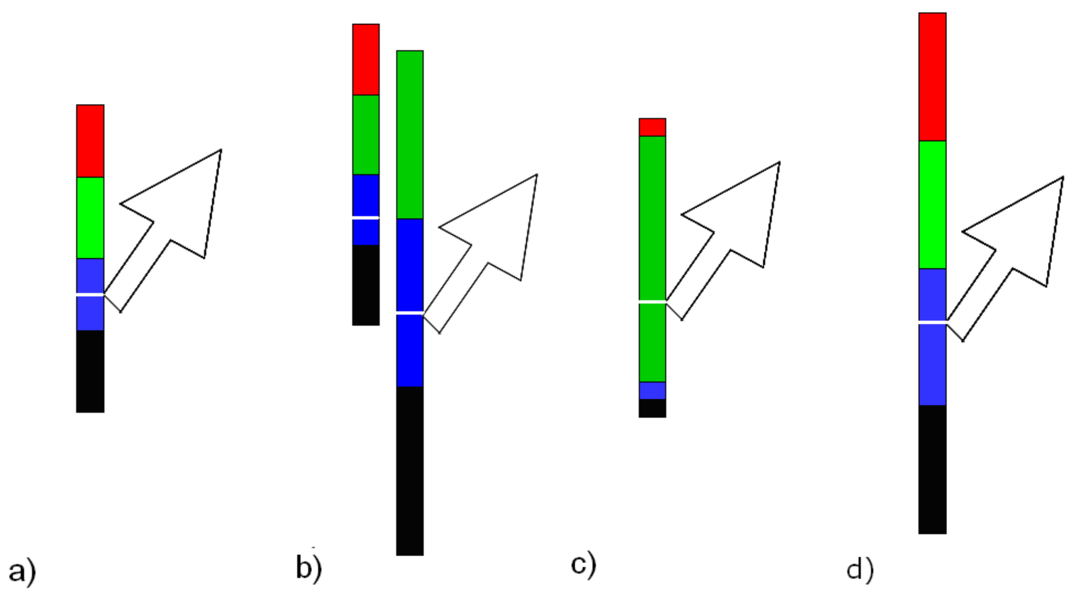

Figure 4.3. a) Overview (OV) (CD ratios 1:0.5 1:1.1 and 1:1.6) b) Overview with direct mapping (ODM)(CD ratios 1:1 with 1:0.5, 1:1.1 and 1:1.6) c) Partial overview (PO)(CD ratios 1:1.3, 1:2 and 1:2.8) d) Direct mapping (DM) (CD ratio 1:1)

4.4 EXPERIMENT 6: Validation of Designs

We ran an experiment to study the performance of the visualizations for layer switching tasks in multilayer input space. Three variables were considered: *cursor type*, layer switching *combinations* and layer *thickness*. We measured movement time and error rates for carrying out the task described below.

4.4.1 Participants

Twelve volunteers, (four female, eight male), aged between 18 and 31, participated in the experiment. All the participants were right handed and controlled the stylus with their right hands. Five of the subjects had previous experience with using large digital tables. All subjects were tested individually.

4.4.2 Procedure

We designed a layer selection task by dividing the space above the display into four discrete horizontal layers of equal thickness. Each layer was represented by a color in the *layer element*. (see Figure 4.4). A square target was displayed in front of the participants at an easily reachable position on the table top display. A small square filled with one of the colors of the other layers (black, green, blue or red) was displayed above it as a target indicator. Subjects had to position the arrow element within the bounding square and move the stylus vertically to the layer corresponding to the color indicated by the target cue. The task started when subjects clicked the stylus button on the target. At this point the target indicator changed its color indicating which layer to switch to. The task finished when the subject clicked the stylus button after moving to the target layer.

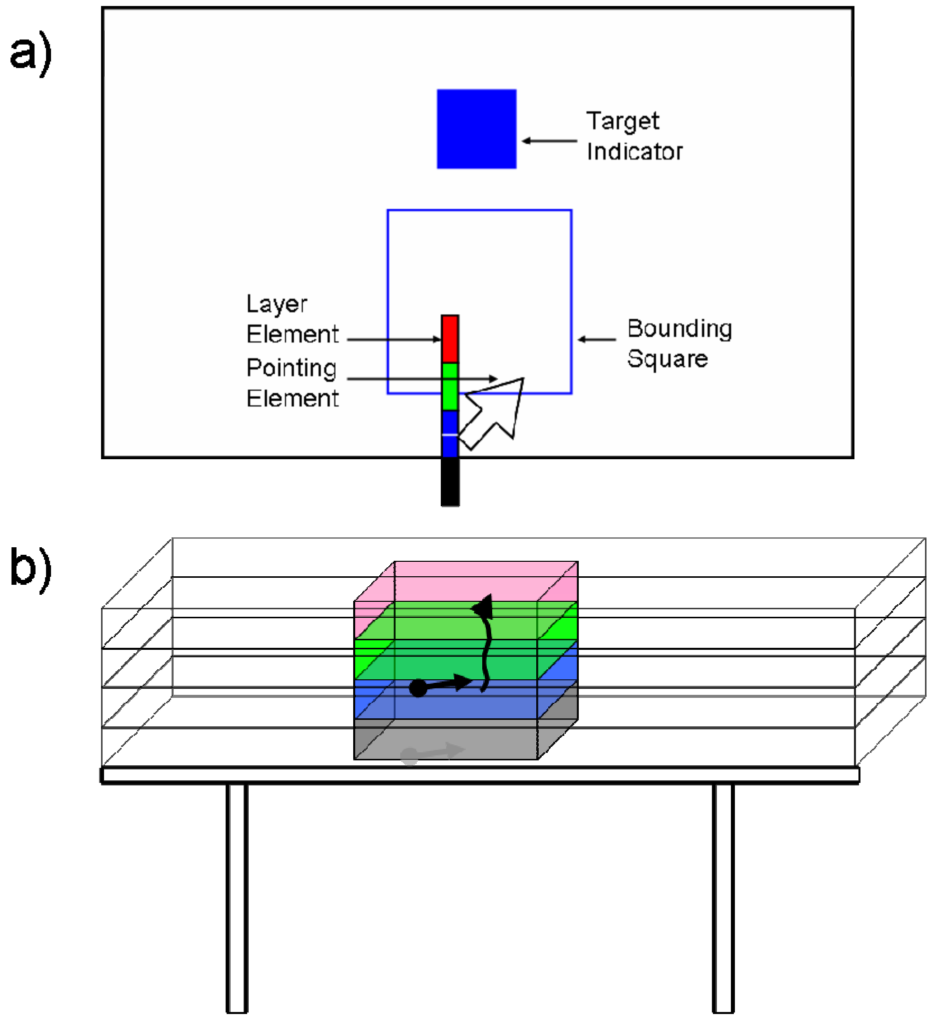

Figure 4.4. A layer selection task. a) Top view b) Front view

The task did not start if the subject clicked outside the bounding rectangle or in a layer not indicated by the target indicator. After starting the task, if the task ended with a click outside the target the task was counted as an error. The task was allowed to continue until the right selection was made. However, the data from error trials were discarded.

Layer thickness information was displayed along-side the cursor and also printed above the target. Changes in layer thickness, visualization type and layer selection were clearly indicated by audio cues.

4.4.3 Experiment Design

We used a repeated measures within-participant design. We controlled the variables type of *cursor* (Overview with direct mapping, Partial overview, Overview, Direct mapping), 8 layer switching combinations among the possible 12 layer switching *combinations* ((0,1),(0,3),(1,0),(1,3),(2,1),(2,3),(3,0),(3,2)) and layer *thickness* (1, 2.5 and 3.5 cm). All the layers had the same thickness. Subjects were treated as random effects. The factors CD ratio and overview and detail were embedded into the type of the cursor. The choice of layer thicknesses is based on the previous steering experiments in layers [36].

The experiment was divided into three blocks. Within each block, trials for each of the three *thickness* and eight *combinations* were presented two times in random order for four *cursors*, resulting in a total of 576 (3x3x8x2x4) trials. The ordering of type of *cursors* in each block was balanced by using a 4x4 Latin Square design. Subjects were trained by randomly presenting 16 sample trials presenting all *cursors* and two *combinations* and layer *thickness.* We measured the task time and number of errors. We also recorded the vertical distance traversed to make the selection. Subjects were asked to rank visualizations based on ease of use, perceived accuracy, and perceived speed, after they completed all the trials.

4.4.4 Results

We recorded Movement Time (MT) from the beginning of the task to the end and also the error rate. We discarded data points more than 3 standard deviations away from the mean MT for the group. Discarded outliers constituted 3.46% of the data points.

The overall error rate was 1.59%, which is similar to the previous studies in the input space. The Overview (OV), Overview with Direct Mapping (ODM), Partial Overview (PO), and Direct

Mapping (DM) visualizations had 1.25%, 1.5%, 1.71% and 1.9% error respectively. Figure 4.5 shows the error rate for all four visualizations. There was a lot of variation in the error rate for different layer thickness across visualizations. The DM cursor had 3.6% error rate which was the highest for the layer thickness of 1.0 cm. The Overview Cursor had the smallest error rate for 1.0 cm layer thickness. For 2.5 and 3.5 cm thick layers DM cursor had the smallest error rate.

The overall error rates for different layer thicknesses are depicted in Figure 4.6 and Table 4.1. The Alpha level for all significance tests was 0.05. Repeated measures analysis of variance (full factorial model) showed a significant difference between error rates for different thicknesses ($F_{2,22}$ =5.901, p<0.009). We did not find a significant difference between error rates for different visualizations or an interaction between visualization and layer thickness ($F_{2,33}$ =0.513, p<0.676), ($F_{6,67}$ =1.286, p<0.276). Post-hoc analysis with Games-Howell criterion reveals that there is no significant difference between error rates for layer thickness 2.5 cm and 3.5 cm while difference between error rates for other layer thicknesses are significant.

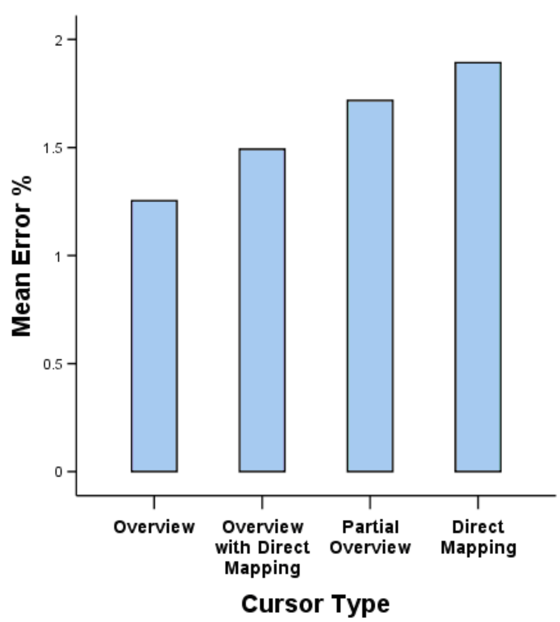

Figure 4.5. Error rate of tasks using three cursors for different target sizes

Table 4.1. Error rate for layer switching visualizations

Thickness (in cm)	OC %	ODMC %	POC %	DMC %
1.00	1.40	2.20	3.04	3.60
2.50	1.40	1.21	1.71	1.10
3.50	0.90	1.00	0.90	0.80

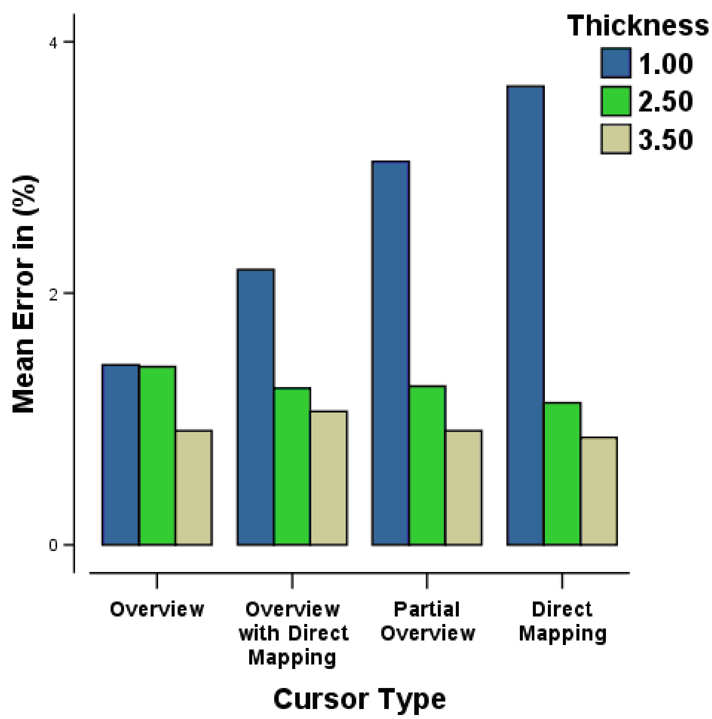

Figure 4.6. Overall error rate for tasks with four different cursors

Repeated measures analysis of variance (full factorial model) of the recorded MT showed an effect of cursor type on movement time *(MT)* ($F_{3,33}$ = 10.197, p<0.001). The effect of thickness on movement time was also significant ($F_{2,6}$ =16.415, p<0.001). Interaction between visualizations and layer thicknesses was also significant ($F_{6,67}$ =11.741, p<0.001). Figure 4.7 plots the mean movement time by visualization type. Post-hoc analysis using Games-Howell criterion for significance showed a significant effect between movement times for all visualizations. However, there was no significant difference between movement times for layers of thickness 2.5 cm and 3.5 cm (p<0.234).

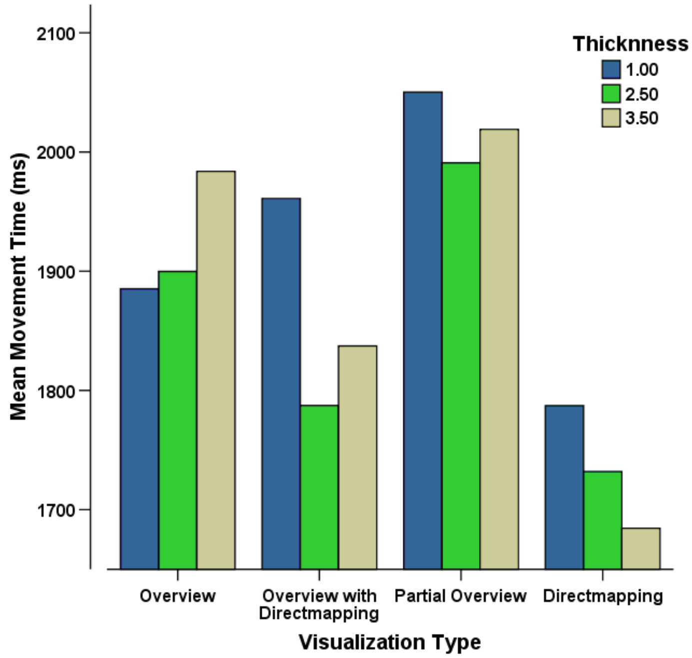

Figure 4.7. Mean task time for tasks using four cursors

The DM visualization was the fastest and the tasks with PO visualization were the slowest. ODM visualization closely follows DM visualization in terms of task time. Although Overview visualization out-performs ODM for the 1.0 cm layer, the difference is not significant.

4.4.5 Subjective Evaluation

All the subjects indicated that the visualizations were easy to use. Figure 4.8 shows the mean of the user rankings for visualizations in terms of ease of use, perceived accuracy and perceived speed. Lowest rank indicates the best choice. Users preferred the Direct Mapped cursor closely followed by the Overview with Direct Mapping. The Partial Overview was the least preferred visualization. We may note that user's perception about visualization differs from quantitative results; more so in the case of error rates.

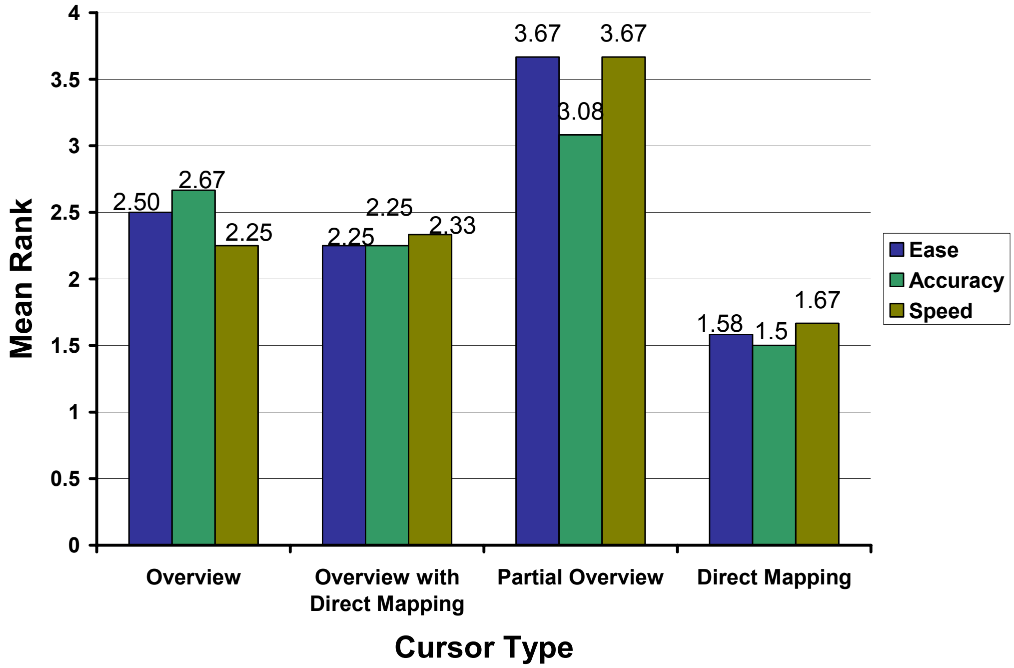

Figure 4.8. Mean rank for different visualizations (shorter bars mean better rank)

Table 4.2. Mean and standard deviation of selection time for visualizations

Dependent Variable: MT				
Cursor Type	Thickness	Mean	Std. Dev	N
Overview	1	1885.21	523.88	545
	2.5	1899.85	505.94	550
	3.5	1983.69	515.24	531
Overview with Direct Map	1	1960.94	520.95	527
	2.5	1787.39	483.87	549
	3.5	1837.29	538.55	555
Partial Overview	1	2050.21	561.09	490
	2.5	1990.91	545.52	542
	3.5	2018.94	544.34	533
Direct Mapped	1	1787.19	524.79	551
	2.5	1732.01	444.10	522
	3.5	1684.38	470.90	577

CHAPTER 5

DISCUSSION

In this chapter, the results of the modeling and the visualization are discussed. Second, we elaborate on the application of our model as well as the layer visualization designs.

5.1 Summary of Findings

5.1.1 The Model Predicts Movement Time for Steering within Layers

The experimental results show that our models (Equation 3.6 and Equation 3.19) can be used to effectively predict movement time when steering through constrained paths in above-the-surface interaction layers. Figure 5.1a graphically represents the relation between the ID and the constraints for steering based on the Accot and Zhai steering model (Equation 2.4). Figure 5.2b shows the relation between the ID and the constraints for steering in layers based on our model (Equation 3.6). A comparison of the graphs shows that the ID values in the models differ considerably for steering lengths more than 10 cm. We can see that the steering ID is more than 30 bits for the tunnels of length is 32 cm when the tunnel is narrow (less than 2 cm). Thus the model clearly reflects the common notion that the difficulty and hence the delay is intrinsic to steering tasks involving narrow longer tunnels. The model clearly reflects the result which shows that there is no significant interaction between Width (*W*) and Thickness (*T*), on *MT*. In Equation

3.6, *MT* is non-linearly related to the ratio of the length of the steering path to the width of the steering path (*A/W*) and the ratio of the length of the steering path to the thickness of the steering path (*A/T*).

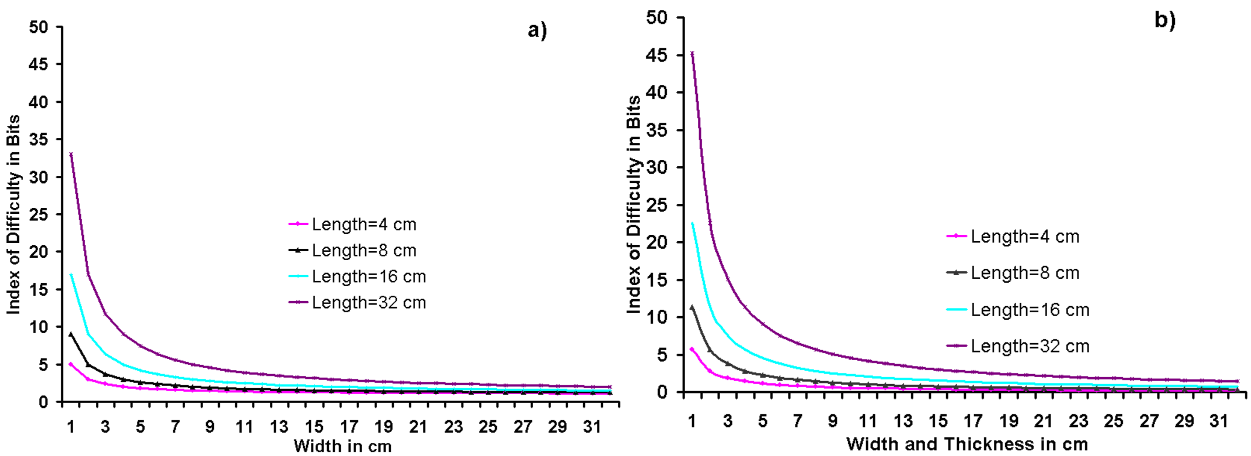

Figure 5.1. a) ID by Width and Length for 2D steering model (Equation 2.3) b) ID by Width, Thickness and Length using model for steering in layers (Equation 3.6)

The experiment also shows that when users are able to rest their hands on a physical surface, the thickness of the layer does not affect performance when a directional constraint is also present. The results of experiments might be dependent on hand being used as a guide. We also observed that there was no significant difference in user performance between layers of thickness 2cm and 2.5 cm. This suggests that for interaction techniques that leverage multiple layers (E.g. Subramanian et al. [20]), the layers could be as small as 2cm when the layer is close to the display surface.

Our results also show that users were more error prone when steering through tunnels of larger path lengths, particularly with a tunnel length of 35 cm. This indicates that if large movements within a layer are required, then designers should increase the thickness of the layer. For the most part however, overall error rates were quite low, indicating that users were able to comprehend the provided cursor visualization. The informal subjective feedback which we received also indicated that the cursor visualization provided an effective indication of the stylus location.

The results also show that the movement time increases as the height of the layer above the surface increases. The high error rate, when steering long tunnels at height more than 10cms, suggests that there is a trade off between the height of the layer and the length of the steering tunnel. When the layer was immediately above the surface, the difference in movement time between layers of thickness 2.5cm and 3.5cm was not significant. However as the height of the layer increased hand could not rest on display; the thickness of the layer had a significant effect on the movement time. Thus the study confirms that a layer thickness of 3.5cms is acceptable for heights up to 15cms.

A η value of 0.16 in Equation 3.13 indicates that the effect layer thickness (T) on movement time is less than effect of tunnel width (W) (See also section 3.6.4). A lower η value may be due to users being allowed to rest their wrist/elbow on the display while performing a steering task. We have seen that in some cases, the effect of thickness (T) on movement time is significant, indicating that the effect of thickness on movement time may vary depending on factors such as height (H). Further work is needed to study steering under several common positions of wrist and elbow on or above the display.

Results indicate that steering was error prone for longer and higher paths, particularly paths of 25cm and paths at the height of 15cm. This indicates that, if height has to increase, thickness should also increase and the steering path should be kept shorter.

5.1.2 Implications for Layer Visualization Design

There are several implications of the layer visualization study:

- The results show that the grid layout approach for multilayer visualization enables easy and efficient interaction.

- Our results present the first empirical evidence to show that a CD ratio without gain enables faster and more accurate layer selection.

An exception to this is the interaction in layers of 1.0 cm thickness. Higher error rates for 1.0 cm layers appear to be because of motor precision issues rather than the visualization. This is supported by qualitative feedback from users who said they preferred a CD ratio with gain for 1.0 cm layer thickness. While studies have suggested that layers should be at least 2.0 cm thick for steering interactions, our study showed that even the layer thickness of 1.0 cm is acceptable for interactions only involving layer switching.

Although a CD ratio without gain is more efficient in visualization, it also causes occlusion by taking up a lot of display area. This renders the visualization less useful in applications. Going by the results of the experiment, we can see that the overall error rate for task completion with the Overview with Direct Mapping (ODM) visualization is close to the error rate of Direct Mapping (DM) visualization and has lesser error rate for 1.0 cm thick layer.

Completion time of the ODM cursor was comparable to DM cursor and was preferred by the users next to the DM cursor. The ODM cursor represents variables such as overview, focus, and multiple CD ratios; therefore we believe that the ODM cursor is a good candidate for application designs in above-the-surface interaction layers (see Figure 5.2).

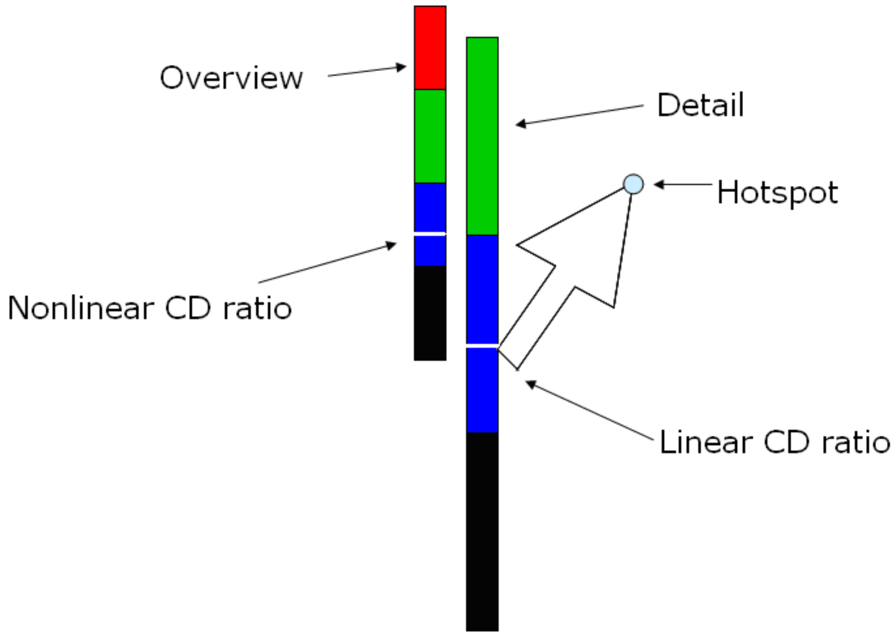

Figure 5.2. ODM Visualization that combines detail, overview and CD ratios

5.2 Applications

The 3D steering model lays a basis for design of interaction techniques using the space above the display surface. Analogous to Fitts' law, the 3D steering model can be used to compare the performance of techniques such as Hover widgets [28], Multilayer interaction techniques [59] and Tracking Menus [23]. It may also be used in performance evaluation of input devices using *b* in Equation 3.6 to calculate the Index of Performance (IP). Interaction techniques can be benchmarked against the 3D Steering model so that they can be readily compared to newly implemented interaction techniques.

Figure 5.2 shows a design that we believe is a good candidate for visualizing multiple above-the-surface interaction layers. Visualization designs proposed in this thesis serve as a basis for custom visualization design requirements of systems such as Tabletops, Tablet PCs and PDAs.

The visualization study also confirms that the grid structure effectively captures the information required for the perception of layers.

CHAPTER 6

CONCLUSION AND FUTURE WORK

This chapter summarizes the solution to the problem addressed in this thesis and discusses the scope for future work. We begin by giving a brief summary of the solution. Then an outline of the main contributions of this research is presented. We conclude by discussing avenues for future work.

6.1 Summary

The problem addressed in this thesis was that designers currently have no model to predict movement time (*MT*) for steering tasks constrained by thickness, width, and length of the path, in above-surface-interaction layers. The problem had two main parts: first, modeling steering in layers; and second, visualizing the layers to provide feedback for the steering task. The solution offered in this thesis was a model to predict *MT*, given by Equation 3.6 and 3.19. The second part of the solution was a set of designs to visualize above-the-surface interaction layers. We designed a series of experiments to validate the predictive model. The experimental results show that our models (Equation 3.6 and Equation 3.19) can be used to effectively predict *MT* when steering through constrained paths in above-the-surface interaction layers. The evaluation of the visualization designs suggest that the grid layout design which combines overview and direct mapping is an effective candidate to visualize layers above the display surface.

6.2 Contributions

Three main contributions of this research are:

- A model to predict movement time for steering in above-the-surface interaction layers (Equation 3.6).
- A model to predict movement time for steering in layers positioned at different heights above the display surface (Equation 3.19).
- An evaluation of designs for visualizing the position of the pen in layers above the display surface.

Other contributions of this research include following design recommendations.

- The length of the steering tunnel in above-the-surface layers should be less than 35.0 cm.
- The tunnel thickness of 1.0 cm is acceptable for tunnel lengths less than 15.0 cm. However, a thickness of 3.5 cm is recommended for longer tunnels and tunnels at the height of 15.0 cm.
- For layer switching interactions, use of layer thicknesses as small as 1.0 cm is acceptable.
- For easy and efficient interaction, we recommend grid layout approach to visualize position of the pen in layers.
- We believe that the CD ratio without gain should be preferred over the CD ratio with gain, to map the pen position for vertical movements, if occlusion due to the size of the visualization is not an issue.

- We recommend a combination of detail and overview, and CD ratio without gain and CD ratio with gain for visualization design in above-the-surface interaction layers, when a direct CD mapping causes occlusion due to the size of the visualization.

6.3 Future work

The intended future work is in two areas: research in modeling more general steering tasks, and research in visualizing above-the-surface layers.

6.3.1 Future Work Related to the Modeling Steering

As this was an initial study on human performance for above-the-surface interactions, we chose to limit our focus to the variables which allowed us to form and validate our theoretical models. In the future, it would be useful to investigate how some of the unexplored factors would affect the results we obtained. For example, in our study we allowed users to rest their hand on the display and use of hand as a guide during the steering task. While using a Tablet PC or table top system, users may be able to do this, but with a vertical display such as an electronic whiteboard, or a small PDA, users may not be able to rest their hand. This would likely reduce the user's ability to control the position of the input device.

Other factors which should also be explored are the arm reach of the user, and the orientation and direction of the tunnel above the surface. Furthermore, it would be interesting to study how the shape of the required path affects performance. In this case when the path is not straight, as it was in our experimental task, the gesture may superimpose finger movements on the hand movement, resulting in increased steering difficulty. We have noted that as the number of variables increases, it gets harder to model interactions through simple relations. This is evident in the large deviation in mean movement time in the experiment investigating the effects of height. Other factors such as wrist and forearm length affect movement time as the height of the layers increases. Understanding this could result in a generalized model of steering through paths, or tubes, in free 3D space [21]. Figure 6.1 shows a generalized steering task in free 3D space.

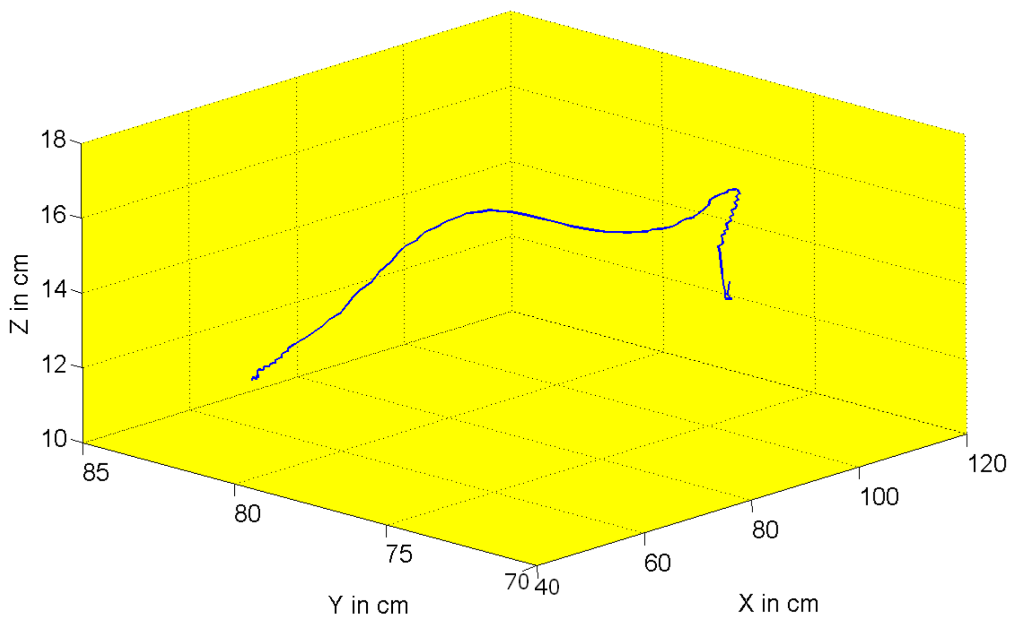

Figure 6.1. A plot of the steering task in the space above the display surface

Although the Accot and Zhai formulations, derived from the perspective of information theory, are successfully applied in HCI, the Drury and Rashevsky formulations approach the modeling problem from the perspective of Biophysics. Drury and Rashevsky consider factors such as reaction time of users, the average angle by which the direction of the car deviates from the true course and the average minimum safe distance from the edges of the steering path. Derivation of the models discussed in thesis is based on the Accot and Zhai formulations. We believe that reanalyzing the models from the perspective of Drury and Rashevsky models will increase our understanding of the performance models and contribute to the development of models capable of addressing limitations in efficiently modeling human-computer interactions.

The model described in this thesis also forms a basis for the design of interaction techniques in above-the-surface layers. Using our models to design new interaction techniques to perform real world tasks should be investigated through future research.

6.3.2 Future Work Related to the Visualization of Layers above the Display

The effect of increasing the size of visual and motor space on layer visualization is yet to be investigated. Research on other possible multilayer designs could result in a framework for layer visualization. We believe that investigation of optimal CD ratio for vertical selection task and layer switching will considerably improve visualization. It would be challenging to explore and design visualization techniques in such scenarios.

Visualization designs explored in this thesis used a simple audio feedback mechanism and did not use audio to represent a layer. We believe that interaction in layers can be improved by designing effective audio feedback along with visualizations. Work is needed to explore the most effective way of providing audio feedback for tasks using our visualization designs. The visualization study described in this thesis explored the visualization designs using a layer selection task. Further research is required to visualize above-the-surface layers for specific real word tasks. We have seen that some visualization designs cause occlusion. It will be interesting to design layer visualizations for tasks with more variables and to address the problem of occlusion in such designs.

In conclusion, we have taken a first step towards understanding human motor performance when steering through above-the-surface interaction layers. We have proposed several models, and validated them through a series of experiments. We explored different visualizations for above-the-surface interaction layers using cursors. Based on user studies and observations we converged on four types of designs to visualize above-the-surface interaction layers. Through controlled experiments we quantitatively analyzed the performance of the visualization designs. We have also suggested a particular design for faster and accurate interaction. We believe that our work will be a significant contribution to the HCI field, as interaction techniques which use above-the-surface layers continue to emerge.

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APPENDIX A

MODELING SUDY – ONE: CONSENT FORM

DEPARTMENT OF COMPUTER SCIENCE

UNIVERSITY OF SASKATCHEWAN

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully and to understand any accompanying information.

Researcher(s): *Sriram Subramanian*, Department of Computer Science
Raghavendra S Kattinakere, Department of Computer Science

Purpose and Procedure:

This study is concerned with modeling movement time when steering through a tunnel of known thickness, width and length on the horizontal work-surface. Modeling movement time would help us design interaction techniques that benefit from the space above the work-surface.

The goal of the research is to determine if there are patterns in tunnel width, length and time when using a stylus to move through a tunnel on a digital work-surface.
The session will require 60 minutes, during which you will be asked to carry out several target acquisition tasks.
At the end of the session, you will be given more information about the purpose and goals of the study, and there will be time for you to ask questions about the research.

There is no known risk to you associated with this study.

The data collected from this study will be used in articles for publication in journals and conference proceedings.

As one way of thanking you for your time, we will be pleased to make available to you a summary of the results of this study once they have been compiled (probably in about four weeks). This summary will outline the research and discuss our findings and recommendations. If you would like to receive a copy of this summary, please write down your email address here.

Contact email address____

Confidentiality: All of the information we collect from you (data logged by the computer, observations made by the experimenters, your questionnaire responses and video or audio recording) will be stored so that your name is not associated with it (using an arbitrary participant number). If audio or video recording is used for data collection, the recording will be such that your personal identity is not compromised. Any write-ups of the data will not include any information that can be linked directly to you. Please do not put your name or other identifying information on the questionnaire. The research materials will be stored with complete security throughout the entire investigation. Do you have any questions about this aspect of the study?

Right to Withdraw: You are free to withdraw from the study at any time without penalty and without losing any advertised benefits. Withdrawal from the study will not affect your academic status or your access to services at the university. If you withdraw, your data will be deleted from the study and destroyed. If audio or video recording is used for data collection, you have the right to switch off the audio or video recorder at any time during the study. In addition, you are free to not answer specific items or questions on questionnaires.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact: Carl Gutwin

Questions: If you have any questions concerning the study, please feel free to ask at any point; you are also free to contact the researchers at the numbers provided above if you have questions at a later time. This study has been approved on ethical grounds by the University of Saskatchewan Behavioural Sciences Research Ethics Board on (insert date). Any questions regarding your rights as a participant may be addressed to that committee through the Office of Research Services (966-2084). Out of town participants may call collect.

Consent to Participate: *I have read and understood the description provided above; I have been provided with an opportunity to ask questions and my questions have been answered satisfactorily. I consent to participate in the study described above, understanding that I may withdraw this consent at any time. A copy of this consent form has been given to me for my records.*

_______________________________ ____________________
(Signature of Participant) (Date)

____
(Signature of Researcher)

APPENDIX B

MODELING STUDY - TWO: CONSENT FORM

DEPARTMENT OF COMPUTER SCIENCE

UNIVERSITY OF SASKATCHEWAN

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully and to understand any accompanying information.

Researcher(s): *Carl Gutwin*, Department of Computer Science (966-4888)
Raghavendra Kattinakere, Department of Computer Science

Purpose and Procedure:

This study is concerned with modeling movement time when steering through a tunnel of known thickness, width, height and length on the horizontal work-surface. Modeling movement time would help us design interaction techniques that benefit from the space above the work-surface.

The goal of the research is to determine if there are patterns in tunnel width, height, length and time when using a stylus to move through a tunnel on a digital work-surface.
The session will require 60 minutes, during which you will be asked to carry out several target acquisition tasks.
At the end of the session, you will be given more information about the purpose and goals of the study, and there will be time for you to ask questions about the research.

There is no known risk to you associated with this study.

The data collected from this study will be used in articles for publication in journals and conference proceedings.

As one way of thanking you for your time, we will be pleased to make available to you a summary of the results of this study once they have been compiled (probably in about four weeks). This summary will outline the research and discuss our findings and recommendations. If you would like to receive a copy of this summary, please write down your email address here.

Contact email address____

Confidentiality: All of the information we collect from you (data logged by the computer, observations made by the experimenters, your questionnaire responses and video or audio recording) will be stored so that your name is not associated with it (using an arbitrary participant number). If audio or video recording is used for data collection, the recording will be such that your personal identity is not compromised. Any write-ups of the data will not include any information that can be linked directly to you. Please do not put your name or other identifying information on the questionnaire. The research materials will be stored with complete security throughout the entire investigation. Do you have any questions about this aspect of the study?

Right to Withdraw: You are free to withdraw from the study at any time without penalty and without losing any advertised benefits. Withdrawal from the study will not affect your academic status or your access to services at the university. If you withdraw, your data will be deleted from the study and destroyed. If audio or video recording is used for data collection, you have the right to switch off the audio or video recorder at any time during the study. In addition, you are free to not answer specific items or questions on questionnaires.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact: Carl Gutwin

Questions: If you have any questions concerning the study, please feel free to ask at any point; you are also free to contact the researchers at the numbers provided above if you have questions at a later time. This study has been approved on ethical grounds by the University of Saskatchewan Behavioural Sciences Research Ethics Board on (insert date). Any questions regarding your rights as a participant may be addressed to that committee through the Office of Research Services (966-2084). Out of town participants may call collect.

Consent to Participate: *I have read and understood the description provided above; I have been provided with an opportunity to ask questions and my questions have been answered satisfactorily. I consent to participate in the study described above, understanding that I may withdraw this consent at any time. A copy of this consent form has been given to me for my records.*

_________________________________ ____________________

(Signature of Participant) (Date)

____

(Signature of Researcher)

APPENDIX C

LAYER VISUALIZATION STUDY: CONSENT FORM

UNIVERSITY OF SASKATCHEWAN

DEPARTMENT OF COMPUTER SCIENCE

UNIVERSITY OF SASKATCHEWAN

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take the time to read this form carefully and to understand any accompanying information.

Researcher(s): *Carl Gutwin*, Department of Computer Science (966-2327)
Raghavendra S Kattinakere, Department of Computer Science

Purpose and Procedure:

This study is concerned with understanding different layer visualizations for digital tables.

The goal of the research is to determine the effects of different layer visualizations using cursors. The session will require 60 to 75 minutes, during which you will be asked to carry out several layer selection tasks.
At the end of the session, you will be given more information about the purpose and goals of the study, and there will be time for you to ask questions about the research.

There is no known risk to you associated with this study.

The data collected from this study will be used in articles for publication in journals and conference proceedings.

As one way of thanking you for your time, we will be pleased to make available to you a summary of the results of this study once they have been compiled (probably in about four weeks). This summary will outline the research and discuss our findings and recommendations. If you would like to receive a copy of this summary, please write down your email address here.

Contact email address____

Confidentiality: All of the information we collect from you (data logged by the computer, observations made by the experimenters and your questionnaire responses) will be stored so that your name is not associated with it (using an arbitrary participant number). Any write-ups of the data will not include any information that can be linked directly to you. Please do not put your name or other identifying information on the questionnaire. The research materials will be stored with complete security throughout the entire investigation. Do you have any questions about this aspect of the study?

Right to Withdraw: You are free to withdraw from the study at any time without penalty and without losing any advertised benefits, including the 10$. Withdrawal from the study will not affect your academic status or your access to services at the university. If you withdraw, your data will be deleted from the study and destroyed. If audio or video recording is used for data collection, you have the right to switch off the audio or video recorder at any time during the study. In addition, you are free to not answer specific items or questions on questionnaires.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact: Sriram Subramanian (966-4888)

Questions: If you have any questions concerning the study, please feel free to ask at any point; you are also free to contact the researchers at the numbers provided above if you have questions at a later time. This study has been approved on ethical grounds by the University of Saskatchewan Behavioural Sciences Research Ethics Board on November 2003. Any questions regarding your rights as a participant may be addressed to that committee through the Office of Research Services (966-2084). Out of town participants may call collect.

Consent to Participate: *I have read and understood the description provided above; I have been provided with an opportunity to ask questions and my questions have been answered satisfactorily. I consent to participate in the study described above, understanding that I may withdraw this consent at any time. A copy of this consent form has been given to me for my records.*

__________________________________ ____________________

(Signature of Participant) (Date)

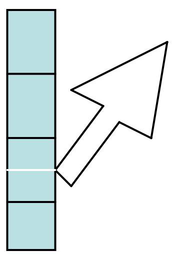
____

(Signature of Researcher)

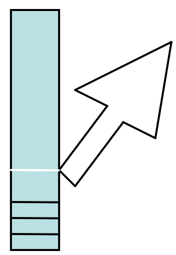
APPENDIX D

LAYER VISUALIZATION STUDY: QUANTITATIVE QUESTIONS

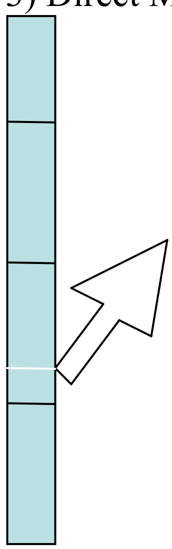
1) Overview Cursor



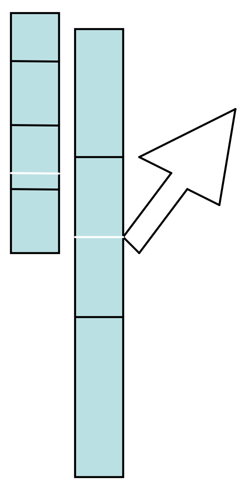
2) Partial Overview Cursor



3) Direct Mapped Cursor



4) Magnified Layer Cursor



Tick the most appropriate option.

1) I found it easy to carry out the tasks using the visualizations.

a) strongly agree b) agree c) neutral d) disagree e) strongly disagree

2) Rank the visualizations based on how easy you think they were to use. (One is easiest, four is less easier)

a) Overview Cursor
b) Partial Overview Cursor
c) Direct Mapped Cursor
d) Magnified Layer Cursor

Why do think, a particular visualization was easy or less easy. Comment on the best and the worst.

3) Rank the visualizations based on how accurate you think you were with visualizations. (One is most accurate, four is less accurate)

a) Overview Cursor
b) Partial Overview Cursor
c) Direct Mapped Cursor
d) Magnified Layer Cursor

Why do you think, you were more accurate or less accurate with a particular visualization. Comment on the most accurate and least accurate visualization.

4) Rank the visualizations based on how fast you think you were with a particular visualization. (One is fastest, four is slower)

a) Overview Cursor
b) Partial Overview Cursor
c) Direct Mapped Cursor
d) Magnified Layer Cursor

Why do you think, you were fast or slow with a particular visualization. Comment on the fastest and the slowest.

5) Comments

VITA

- 1979 Born in Mudugodu, Karnataka, India
- 2002 B.E. in Computer Science and Engineering, PDA College of Engineering, Gulbarga, Visvesvaraya Technological University, Belgaum, Karnataka, India
- 2002-2004 DSP Engineer, EPIGON Media Technologies Pvt Ltd, Bengaluru, India
- 2004-2005 Project Engineer, WIPRO Technologies Ltd, Bengaluru, India
- 2005-2006 DSP Engineering Consultant, Philips Applied Technologies, Eindhoven, The Netherlands, and Leuven, Belgium