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Wayfinding Techniques for Multiscale Virtual Environments

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Dissertação apresentada como requisito parcial à obtenção do grau de mestre em Ciência da Computação

Orientador: Prof. Dr. Márcio Sarroglia Pinho

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Aos meus pais.

Abstract

Wayfinding in multiscale virtual environments can be rather complex, as users can and sometimes have to change their scale to access the entire environment. Hence, this work focuses on the understanding and classification of information needed for travel, as well as on the design of navigation techniques that provide this information. To this end, we first identified two kinds of information necessary for traveling effectively in this kind of environment: hierarchical information, based on the hierarchical structure formed by the levels of scale; and spatial information, related to orientation, distance between objects in different levels of scale and spatial localization. Based on this, we designed and implemented one technique for each kind of information. The developed techniques were evaluated and compared to a baseline set of travel and wayfinding aid techniques for traveling through multiple scales. Results show that the developed techniques perform better and provide a better solution for both travel and wayfinding aid.

Keywords: Virtual Reality; 3D Interaction.

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VR	Virtual Reality	23
VE	Virtual Environment	23
HMD	Head Mounted Display	24
CRT	Cathodic Ray Tubes	25
LCD	Liquid Crystal Displays	26
VIVED	Virtual Visual Environment Display	26
CAVE	CAVE Virtual Automatic Environment	26

Contents

1 Introduction

Virtual Reality (VR) is a human-computer interface involving real-time simulation and interaction through multiple sensory channels such as vision, hearing and touch [Burdea and Coiffet 2003]. The maturing of the technology behind it allows new applications to be researched and developed. Through computer generated three-dimensional environments, known as the Virtual Environments (VE), and specific devices, VR can bring the benefits of immersion and more natural interaction in reproductions of real or imaginary situations.

Interaction is the process of communication between users and computer, where users indicate, through actions, their intentions and their goals and the computer responds by changing a state of the system or presenting information about the world [Hix and Hartson 1993]. In VEs, the interaction process can be classified into selection, manipulation, control and navigation.

Navigation consists of actions that allow users to change their position and orientation, know as travel, and the planning and choice of routes to be followed within the environment and the cognitive process of building spatial knowledge, known as wayfinding [Bowman et al. 2005]. Navigation tasks can be divided, according to their goals, in three categories: **exploration**, characterized by the free navigation in the environment; **based search**, where the user must go to a specific place in the environment or look for a specific object, and **maneuver**, when the user needs more precise positioning [Bowman and Hodges 1999]. When selecting the navigation techniques that will be used, it is important to take into account the type of tasks users will have to achieve.

Presenting large amounts of information at the same time can cause problems for the interfaces in general, because there is too much to see and navigation becomes difficult [Furnas and Bederson 1995]. For more than a decade, researchers have been trying to solve this problem by developing techniques for structuring information on different **levels of scale** [Zhang and Furnas 2005]. The levels of scale are determined by their semantic content, and have specific settings according to the amount and size of information users will be able to see and interact with.

MultiScale Virtual Environments (MSVEs) contain several hierarchical levels of scale in the same environment, in which smaller scales are nested within larger scales [Kopper et al. 2006]. In MSVEs, the levels of scale can be either a place or an object. For example, cities are nested in a state, states are nested in a country, and so on. Being at the country level of scale, it would be possible to see all the states in a country and have a broader view of the VE, but being at the human level of scale, it would be possible to walk around a city and look at the details of the texture of a building.

Nevertheless, the understanding of such structures can be complicated. For example, in the world we know, objects range from $10^{-16}m$ (size of the smaller elementary particles) to $10^{26}m$ (size of the universe). These levels of scale are far from what a human being can interact with, which range from millimeters ($10^{-3}m$) to tens of meters ($10^{1}m$). This fact makes it difficult or even impossible to observe and understand these different levels of scale, and also to interact directly with many of the existing structures in the real world [Zhang and Furnas 2005]. This is also true in a VE, as the use of only one point of view of the environment can make it difficult for users to understand the **context** in which they are, as the human scale puts most of the environment out of their reach [Stoakley, Conway and Pausch 1995].

For this reason, users need a set of techniques that allow for the adjustment of their size and that also automatically adjust navigation parameters when they change their level of scale, such as users' height in the environment (if there is a floor), the speed in which they travel, what they can reach or see and, if using stereo, the distance between the users' eyes.

Although researchers have investigated methods for traveling between different levels of scale [Song and Norman 1994] [Kopper et al. 2006], there is still a need for better wayfinding aids to allow users to make sense of these complicated environments. Thus, the main question that remains is how well the existing techniques can provide wayfinding aid. Depending on the number of levels of scale in the MSVE, it may be too hard for users to figure how to get from one level of scale to other levels. Research in this kind of environment is necessary to remedy this.

Thus, the main objectives of this research are to provide a clear understanding of how the human process of wayfinding works in MSVEs, to identify what information is necessary to navigate effectively through different levels of scale in MSVEs and to design and implement navigation techniques for MSVEs that combine both travel and wayfinding aid information. This work was partially done at the Virginia Polytechnic Institute (Virginia Tech), in collaboration with Dr. Doug Bowman [1].

This document is organized as follows: Chapter 2 shows an introduction to Virtual Reality, necessary for the understanding of the techniques and physical devices used. Chapter 3 presents a detailed study on the related work: first on navigation in VEs in general; then the existing applications for MSVEs and the navigation techniques developed using multiple scales and the ones developed to navigate between different scales;

[1] http://people.cs.vt.edu/ bowman/

and finally the classification of information needed for navigating in such complex environments. Chapter 4 describes the research testbed; the changes made to the application developed by Kopper [Kopper et al. 2006], and how the existing techniques were changed. Also, it explains how the new techniques were developed, how they work and how they show the information classified in Chapter 3. Chapter 5 presents all the aspects involved in the user study: the apparatus used, the procedure of the formal study, metrics, the informal study made before the experiment, the hypotheses, the tasks and the results of the formal study. Chapter 10 discusses the results and highlights the conclusions.

2 Virtual Reality

According to Burdea [Burdea and Coiffet 2003], Virtual Reality (VR) is an interface between user and computer that involves simulation in real time and interaction through multiple sensorial channels, as vision, hearing and touch. Through three-dimensional environments and specific devices, the idea behind VR is to provide the immersion in reproductions of real or imaginary situations to the user. The amount of devices and their capacity to stimulate the users' senses determines the level of immersion of a Virtual Environment (VE).

VEs are defined by Pinho [Pinho 2000] as dynamic three-dimensional scenes, stored in a computer and displayed in real time using computer graphics techniques. These computer generated environments are dynamic because they can be modified as users move and interact with objects.

Interaction is the process of communication between user and computer, in which they indicate, through actions, their intentions and their goals and the computer responds by changing a state of the system or presenting information about the world [Hix and Hartson 1993]. It involves and depends on concepts such as the interaction resolution and the number of degrees of freedom that one device or interactive technique provides to the user [Pinho 2000]. The resolution of interaction is the time interval between one input capture and the other. It is important to increase the interaction resolution when users need bigger precision, such as when they are doing precise object positioning. The number of degrees of freedom is the number of axles on which the user can simultaneously dislocate or rotate himself or the objects in the scene during the interactive process. The interaction also depends on which devices will be used and on the task that will be given to the user.

In VEs, interaction techniques can be divided into **control**, **selection**, **manipulation** and **navigation** [Bowman et al. 2005]. Control specifies actions to change a state of the system or the way the interaction techniques will work, using menus to input commands to the system. Selection is the action of selecting an object or a set of objects inside of a VE. Manipulation is the action of changing attributes of the selected object, such as the position and orientation. Navigation is the act of moving inside the VE, known as **travel**, and the cognitive process of defining a path to go from one place another, known as **wayfinding**.

VR can be applied to several areas, such as the simulation and project of vehicles, entertainment, architecture, training, medicine and psychology. Moreover, as Sutherland affirmed, VR allows users to experience situations that are not realizable concepts in the real world, that is, environments in which physical limits do not exist [Sutherland 1965].

In the next section, a brief timeline of the evolution of VR will be presented. After, some of the devices used currently will be presented.

2.1 Timeline

The first VR-like experiments date of 1957, before the definition of the term, when Morton Heilig invented a machine named as Sensorama [Heilig 1962] (Figure 1). It simulated a motorcycle ride in the city of New York, generating colorful and livened up three-dimensional pictures, stereo sound, smell, wind and seat vibration. In 1960, Heilig patented another invention, a **Head Mounted Display** (HMD) [Heilig 1960] (Figure 2).

Figure 1: The first VR-like experiment, known as Sensorama, which simulated a motorcycle ride
Source: <http://www.artmuseum.net/w2vr/timeline/Heilig.html>.

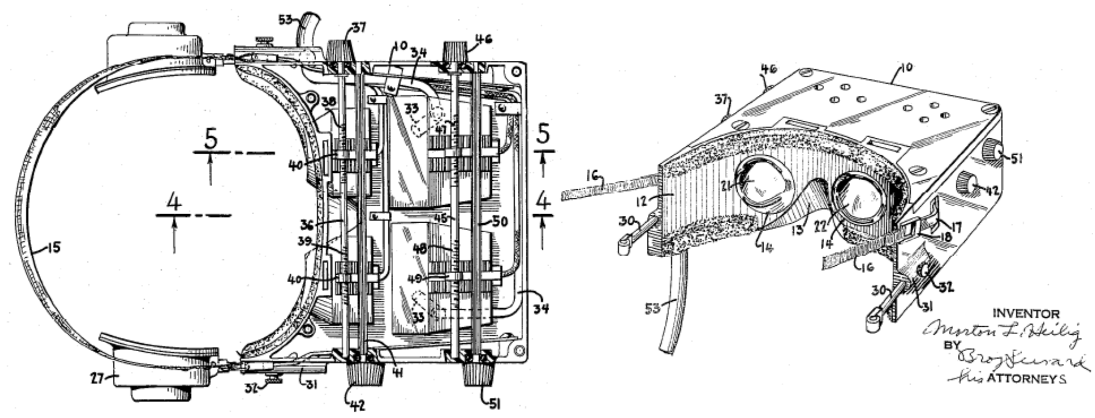

Figure 2: The HMD, idealized by Morton Heilig in 1960
Source: [Heilig 1960].

In 1961, Charles Comeau and James Bryan, then working for Philco Corp., invented the Headsight System, the first HMD that tracked head movement [Comeau and Bryan 1961]. It reproduced pictures generated by a camera that followed the movements made by the head of the user.

Ivan Sutherland published the article “The Ultimate Display” [Sutherland 1965] in 1965, that served as reference for the development of many devices and the definition of VR. Sutherland considered the use of pictures generated by a computer instead of filmed scenes, and suggested that such fact would make interaction possible in environments without physical restrictions. In 1968, Sutherland used two Cathodic Ray Tubes (CRT) displays mounted on the users’ head and constructed the first HMD with the capacity to reproduce computer generated images, continuing the work idealized by Heilig [Sutherland 1968].

In 1967, Frederick Brooks Jr developed the first VR system featuring haptic feedback [1], in which the user used a small knob to move a platform in two dimensions [Brooks et al. 1990]. The position of the platform was detected by the system, and the movements were reproduced in a screen. Depending on the position, different forces were applied to the knob the user was holding. The system was tested as method of teaching force fields with a group of physics students, who had to identify the force fields generated by the system.

In 1976, Defanti and Sandin invented the first glove for monitoring hand movements, known as the **data-glove** (Figure 3) [Rauterberg 2002]. The equipment used light sensors inside translucent tubes that were placed through the extension of all fingers. Each one of these tubes contained, in one extremity, a light source and, in the other, a photocell. As users move their fingers, the light intensity that arrives at the photocell is used to determine finger movements.

[1] Burdea defines haptic feedback as the feedback of force (weight, rigidity and inertia of objects) and tactile feedback (smoothness, temperature and attrition) [Burdea and Coiffet 2003].

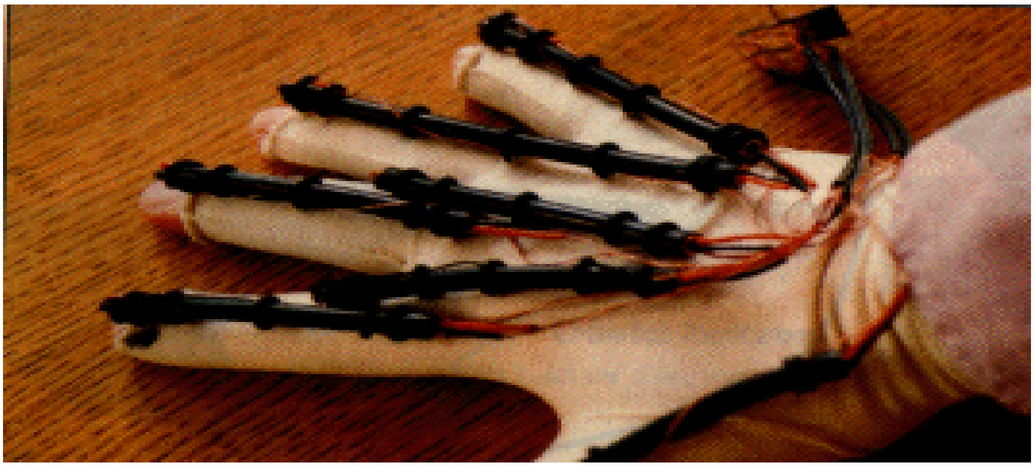

Figure 3: Data-glove, which users light sensors to calculate fingers' movements
Source: <http://www.inf.pucrs.br/~pinho>.

In 1979, Frederick Raab developed his idea for tracking position and orientation, based on the application of orthogonal magnetic fields [Raab et al. 1979], that is used in tracking systems developed by the Polhemus[2] company.

In 1981, NASA Researchers developed a prototype of a HMD using Liquid Crystal Displays (LCD), in a project called Virtual Visual Environment Display (VIVED) [Burdea and Coiffet 2003]. Using a computer capable to generate three-dimensional images and the Polhemus tracking system, this HMD was part of what was considered as the first immersive VR system. The sensors tracked head movements and the computer generated the images of a Virtual Environment, displaying the images with the HMD in stereo.

In 1992, Carolina Cruz-Neira described the CAVE (CAVE Virtual Automatic Environment) [Cruz-Neira et al. 1992], a system that involves a physical environment formed by walls that surround the user, in which stereoscopic images are projected[3] of the virtual environment (Figure 4). As the user moves around in the environment, the point of view is updated and the stereoscopy is adjusted.

2.2 Devices

The VR devices have the goal of increasing the users' level of immersion. They stimulate different human senses, as sight, touch and smell, and also allow to capture actions performed by users, as the movements of the hands, fingers, arms, eyes, and lips.

[2] http://www.polhemus.com
[3] Stereoscopy is the union of two images formed of slightly different points of view to accent the effect of three-dimensional vision.

Figure 4: A user in a CAVE, which uses projection displays to surround the user and increase immersion
Source: <http://resumbrae.com/ub/dms259_s06/12/>.

Between the visualization devices, those that can be highlighted are the HMD, the shutter glasses and the projection-based displays. The HMDs is a helmet that is mounted on the head of the user with individual displays for each eye. Usually, it is coupled with a position and orientation tracker, so the movements of the head can be used by the system to generate the images of the virtual environment based on the user's point of view. Shutter glasses are glasses with two LCD lenses, one for each eye, that can be dark or translucent, and operate in synchrony to a computer. When the computer shows the image of the right eye, the lens of the left eye is darkened and the lens of the right eye becomes transparent. The opposite occurs when the application displays the image of the left eye. An example of a projection-based display system is the active stereoscopic projection, which uses the shutter glasses, usually used in systems like the CAVE, mentioned in the previous section.

Burdea [Burdea 1999] says that **haptic feedback** is essential for VR, because it increases users' awareness of their body position inside the VE. A device that is commonly used in this area is the PHANTOM[4] (Figure 5), composed by a mechanical arm that has force feedback and movement tracking. Another solution, presented for Fujii [Fujii and Furusho 2005], is a glove that simulates tactile and force feedback with cables to track and magnetic brakes to restrict finger movements.

[4]http://www.sensable.com

Figure 5: An example of a device that provides haptic feedback, known as Phantom
Source: <http://www.sensable.com/haptic-phantom-omni.htm>.

The generation of olfactory stimulus is made through the vaporization or diffusion of sources of odor in liquid or solid form [Nakaizumi et al. 2006]. An interesting olfactory simulator, presented by Yamada [Yamada et al. 2006], uses mobile devices to represent odor spatiality, creating the concept of odor fields. The user walks inside of a determined area with the equipment, and, as he changes his position, feels different odors. To generate the different essences, four engines were used to pump the air, and three of them were perfumed. A photo of the device that is mounted to the head of the user to present the odors can be seen in Figure 6.

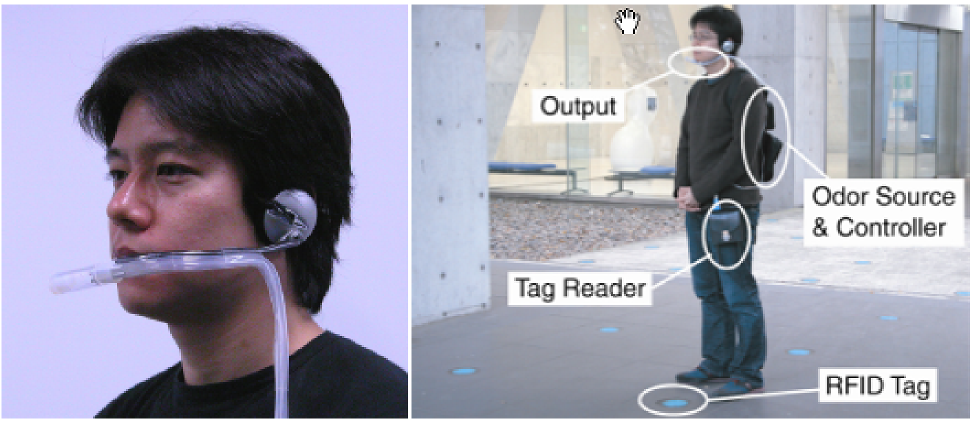

Figure 6: User wearing the odor-presenting unit and the configuration of the odor field presentation system
Source: [Yamada et al. 2006].

Other types of devices used in VR applications are the input devices, such as Joysticks and Wands, and the position and orientation trackers, which can used to track movements of the head or even the fingers of the user.

3 Related Work

This chapter presents a literature review on all work related to the research presented in the next chapters. It is divided into three sections: Navigation in Virtual Environments, which presents an introduction on navigation; MultiScale Virtual Environments, which presents a survey on the existing applications and navigation techniques for this kind of environment; and Understanding Wayfinding in MSVEs, which presents a summary of the issues when navigating in MSVEs and what we identified as needed to solve these issues.

3.1 Navigation in Virtual Environments

Navigation is an important task in VEs, and it has as goals movement, orientation and the acquisition of space knowledge of the user. The navigation tasks can be subdivided into three categories: **exploratory**, characterized by the free navigation for the environment; **search**, when the user must get to a specific place or is looking for a specific object in the environment; and **maneuver**, when a more precise positioning is necessary [Bowman and Hodges 1999]. When choosing or developing a new navigation technique, it is important to take into consideration the tasks that are going to performed.

Bowman [Bowman et al. 2005] divides the task of navigation in a VE between the movement and definition of orientation of the user's point of view, known as **travel**, and the planning and choice of the routes to be followed inside the environment, known as **wayfinding**.

3.1.1 Travel

Travel is one of the most common tasks in a VE, and it is important that we define some of its basic components. By doing so, all aspects and components of the problem can be well understood. The components detailed in this section are the virtual observer, the reference used for travel, the navigation metaphors that can be used and the characteristics of the movement of the virtual observer [Pinho 2000].

The **virtual observer**, also defined as the camera, is the representation of the user in the environment. The observer is defined by three parameters: position, point of interest and field of view (Figure 7). The position is the localization of the user in the environment and the point of interest is the place the user is looking at. The field of view determines how much of the environment the user will be able to visualize using the other two parameters.

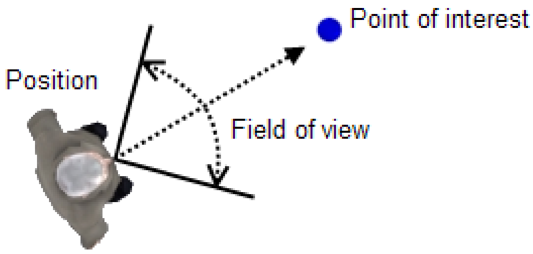

Figure 7: Representation of the observer in a VE, showing the position, point of interest and field of view.

The reference used for navigation defines the coordinate system on which the user will travel. As well as in the real world, the user can use his own coordinate system for movement, independent of objects and the scene. On the other hand, by using the coordinate system of an object, the user can easily accomplish tasks that involve interaction with that object, as shown in Figure 8.

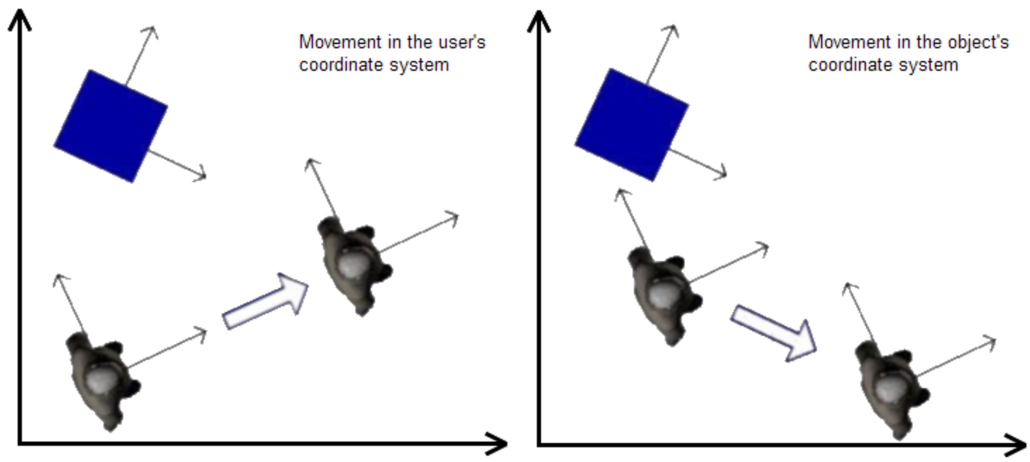

Figure 8: User traveling in her own coordinate system and in the coordinate system of an object.

The control of the observer's movements in the VE can present some specific characteristics, depending on the type of application, such as a fixed point of interest and the alignment of the position and the point of interest with the ground. Usually, the point of interest moves as users move. However, when the interest of the user is an object, or a set of objects, it can be fixed. The Figure 9 illustrates the difference of movement with a fixed point of interest and with a moveable point of interest.

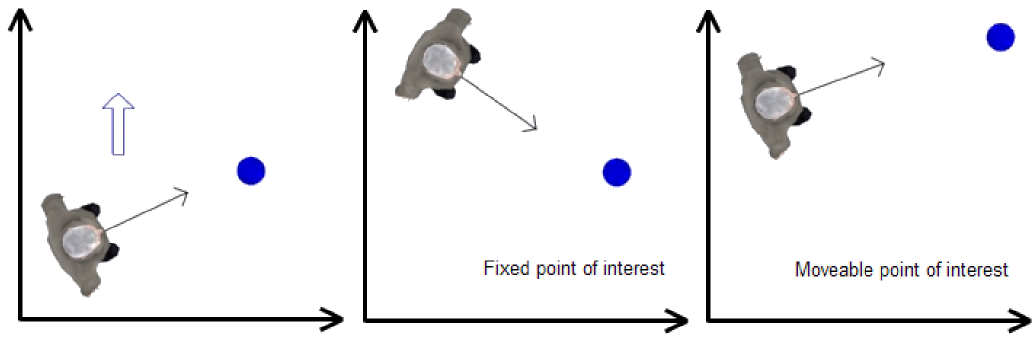

Figure 9: Difference between traveling with a fixed and a movable point of interest.

The alignment of the position and point of interest of the user to the ground can be a desirable feature to applications which simulate walking. The Figure 10 shows the difference of the movement with and without the adjustment of the height in relation to the ground, and also the behavior that the observer would have when lining up its point of interest to the ground.

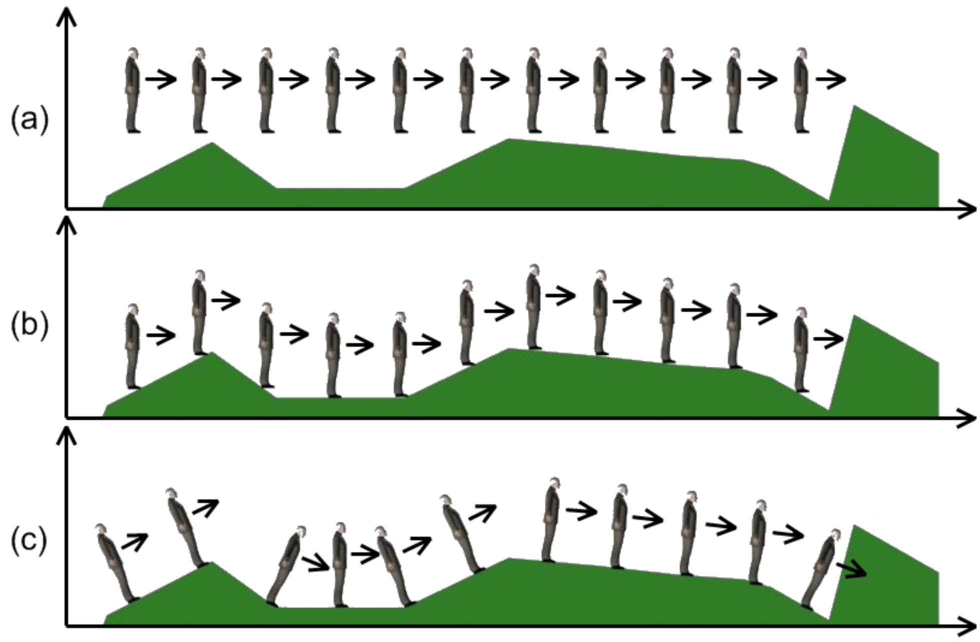

Figure 10: Difference of moving without (a) and with (b) the adjustment of the height relative to the ground, and also the behavior that the observer would have when lining up her point of interest to the ground (c).

3.1.1.1 Travel Techniques

Bowman [Bowman et al. 2005] classifies the existing travel techniques into five groups: physical motion, that consists on the direct mapping of the movements of the user; pointing/steering, in which the user must point at the direction to which he wants to go; route planning, characterized by the previous definition of path to be taken; target-based, in which the target location is selected by the user; and by manipulation, which uses methods of selection and manipulation for the displacement.

Furthermore, it is possible to cite some characteristics that must be taken into consideration for traveling, such as the adjustment of scale and speed, the distance to be covered and number of turns. **Scale adjustment** is used, for example, to diminish the physical space used by the natural walking technique [Interrante, Ries and Anderson 2007]. **Speed adjustment** during navigation allows the user to slow down to observe important parts of the VE or to speed up when traveling through a part of the VE that has already been covered or is less interesting [Pinho 2000]. The **number of turns** that the user has to make while covering the VE is another important factor, because the travel technique can influence directly on the time that the user will spend to turn.

Bowman [Bowman, Koller and Hodges 1998] defines five categories of metrics for evaluating travel techniques: measures of performance to directly compare different techniques; task characteristics that can affect user's performance; environment characteristics that must be considered; user characteristics that can affect the way she uses the techniques; and system characteristics that can increase immersion.

3.1.2 Wayfinding

Wayfinding is a decision-making process, in which the user extracts information from the environment, forming mental representations of this environment [Darken, Allard and Achille 1998]. The representations, also called **cognitive map**, are kept unconsciously and are used during the navigation process to travel. Wayfinding tasks are composed of all the situations in which the user searches for something inside the VE, either a specific place or an object, and when the user is acquiring spatial knowledge.

The wayfinding interaction techniques have as objective to aid the wayfinding process, and can be classified into **user-centered** and in **environment-centered** [Bowman et al. 2005].

3.1.2.1 User-Centered Wayfinding Aid Techniques

Techniques centered in the user are based on the human sensorial system, that is, they are related to the capacity of sensorial stimulation. Some of the factors centered in the user that can assist wayfinding in VEs are:

- field of view;
- movement tips;
- multi-sensorial output;
- sense of presence in the VE;
- search strategies.

The adjustment of the **field of view** involves a basic characteristic travel, described in Section 3.1, that indicates how much of the environment the user can view using the visualization device. A smaller field of view can be harmful, because it demands more head movement to get information about the environment. A bigger field of view reduces the movement necessity and facilitates the space and environment understanding [Czerwinski, Tan and Robertson 2002].

Movement tips are tips provided by the system so that the user perceives her own movement, through the real or virtual environment [Banton et al. 2005]. They can increase depth perception and provide useful information so that the user can locate herself in the environment.

When making use of **multi-sensorial outputs** to provide wayfinding aid, it is possible, for example, to indicate directions and estimatites of distance between the user and the objective. In the work developed by Yamada [Yamada et al. 2006], the odor of determined foods indicate the direction of specific places in the VE, and the intensity of this smell indicates the distance (Figure 11).

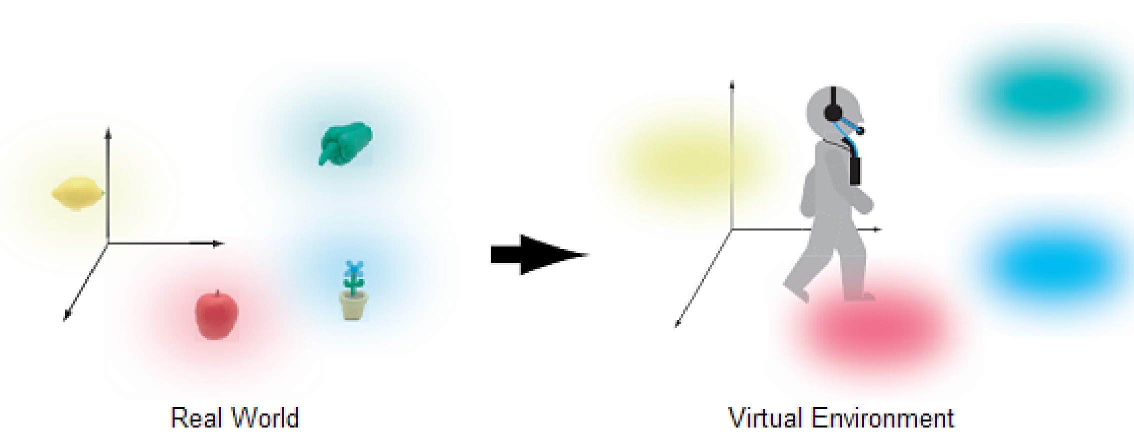

Figure 11: Comparison between the odors existent in the real world and the ones created in the VE
Source: [Yamada et al. 2006].

Presence, defined as the sensation that the user has of being in the VE, is an important factor so that the tips provided by the system can be used. In order to increase this sensation, it is possible, for example, to show the user's body inside the VE [Usoh et al. 1999].

Other factors that can assist the user in navigation are **search strategies**. For example, to use a technique that allows the user to go up to a certain height to have a complete view of the environment can help the user to locate her objectives and to determine possible ways to get there [Darken and Sibert 1996].

3.1.2.2 Environment-Centered Wayfinding Aid Techniques

The wayfinding aid techniques centered in the environment involve visual aspects of the VE, and consist on the addition of artificial tips to the environment as a part of it. Are part of the set of artificial tips:

- artificial landmarks;
- natural landmarks;
- maps;
- compass;
- trail;
- signs.

Artificial landmarks serve to keep spatial orientation and to indicate the localization of objectives [Darken and Sibert 1996]. The landmarks that have a objective to keep the orientation, called global artificial landmarks, can be seen in any point of the environment. For example, it is possible to place an marker in specific point in the VE so that the user can use it as a reference to get to other places. The landmarks that have as objective to indicate localization, known as local artificial landmarks, help in the decision process by providing information about the user's current localization and the localization of the user's objectives. As can be seen in the Figure 12, a box was placed in the environment to indicate the localization of the objective.

Natural landmarks are common objects, as buildings, poles, or even chairs and tables (Figure 13). They have the function to represent something in the VE, and can be used to inform to the user some aspects of the environment, such as the scale of the environment and distance between objects [Burigat and Chittaro 2007]. For example, in applications that allow the user to fly, it is possible to use mountains to indicate to the user the direction of the ground.

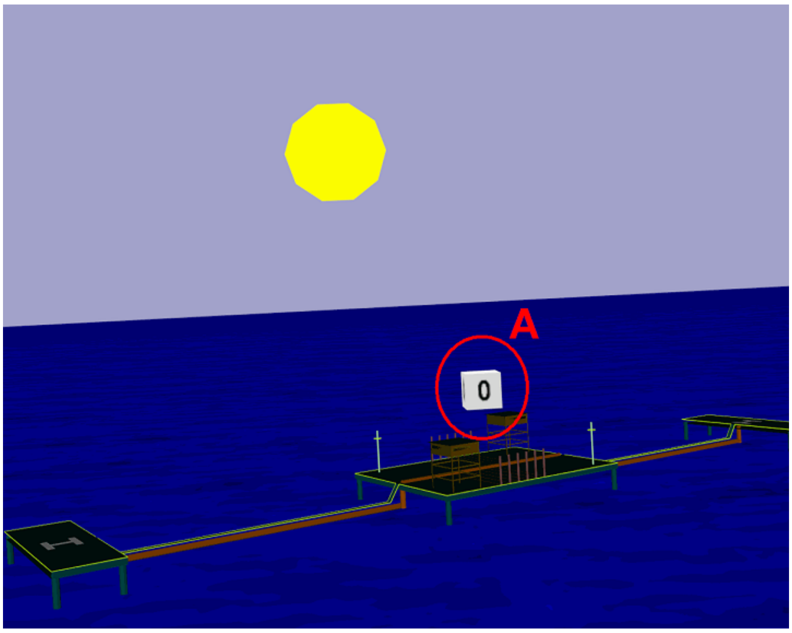

Figure 12: Artificial landmark indicating the objective, highlighted by the letter A
Source: [Darken and Sibert 1996].

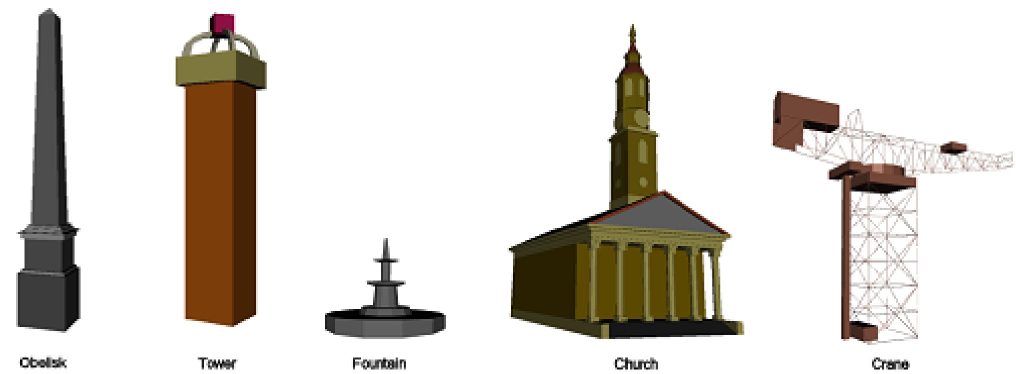

Figure 13: Examples of natural landmarks
Source: [Burigat and Chittaro 2007].

There are different ways of using **maps** as an aid to wayfinding in VEs. For example, in large-scale VEs, a general map of the environment may not reproduce the desired information, becoming necessary the use of more than one scale of the same map. By doing this, it is possible to show the general localization in the VE and regional details of the user's current position. The way the map is presented to the user can also affect performance. Darken [Darken and Cevik 1999] demonstrates that the map is more effective when it is presented in the same orientation of the user (Figure 14).

A **compass** in a VE can either indicate the orientation of the user relative to the environment (e.g.: the north of the environment), or the direction to get to a specific place [Burigat and Chittaro 2007]. Figure 15 represents the use of a two-dimensional arrow to indicate the direction of an objective.

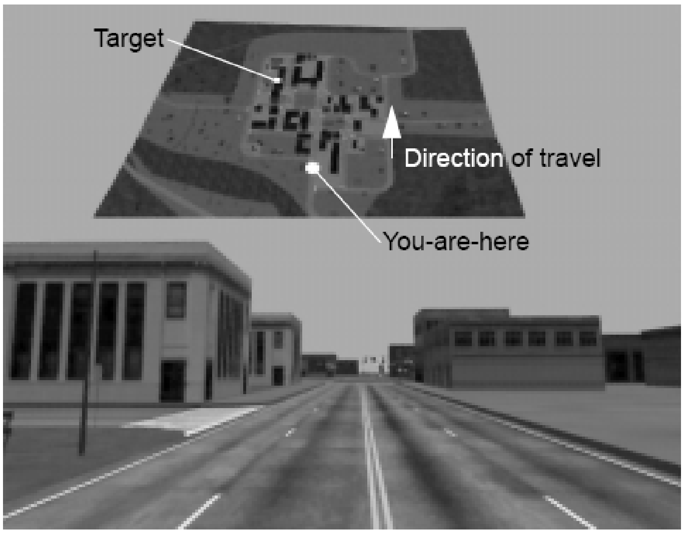

Figure 14: Map of a VE, with markers indicating the objective and the localization of the user
Source: [Darken and Cevik 1999].

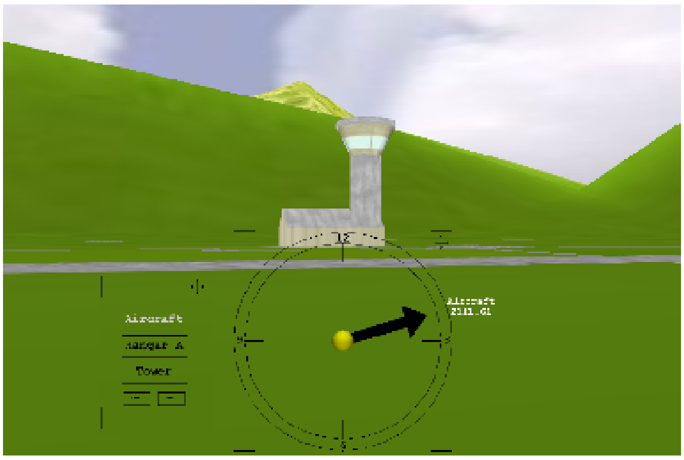

Figure 15: Compass in 2D indicating the objective
Source: [Burigat and Chittaro 2007].

Trails show the paths already covered by the user using "marks" in the VE, assisting the user to accomplish exploration tasks [Ruddle 2005]. They can be directly added to the environment, as can be seen in Figure 16, or indicated in a map. Trails can also provide information on the direction of navigation at the time the user passed by the place marked [Grammenos et al. 2002].

Signs are messages affixed to the environment that can indicate directions to be followed and the localization of specific places in the environment (Figure 17). Cliburn [Cliburn and Rilea 2008] compared signs to a north-up map, and found that signs help users to perform better.

Figure 16: Trail indicating places where the user already passed by
Source: [Ruddle 2005].

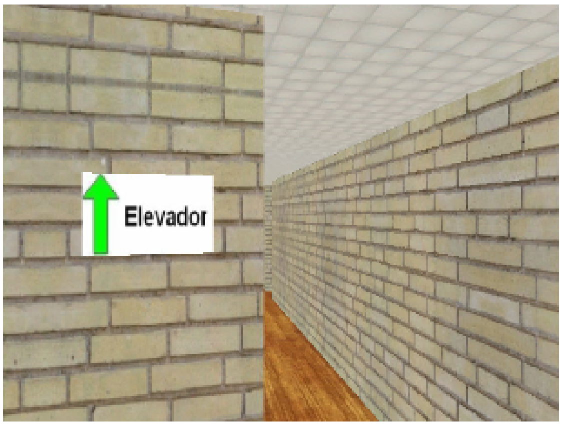

Figure 17: Sign used to indicate a possible path to arrive at the objective
Source: [Bacim, Trombetta and Pinho 2007].

3.1.2.3 Evaluation

Ruddle [Ruddle and Lessels 2006] considers three groups of metrics that can be used, which help researchers to determine more precisely if the technique helped in the wayfinding process. The groups of metrics are:

- metrics based on the user's performance;
- metrics based on the user's physical behavior;
- metrics based on the analysis of the user's decision-making process.

The effectiveness of a technique and how it compares to other techniques can be evaluated by measuring the **user's performance**. Quantifiers that can be used include the time spent, the distance covered and the number of errors when performing the tasks. These metric had been used by Ruddle [Ruddle 2005] in the evaluation on how the trail technique affects the user's performance for the first time and subsequent navigations in a VE.

Metric based on the **evaluation of the user's physical behavior** consists on the analysis of the user's actions while accomplishing a task. This type of metric is less explored, what causes a lack of consensus in the definition of which data must be observed. The evaluation of the behavior can be divided into three categories: **actions**, divided into the analysis of the movement patterns and the paths taken to find the objective, analysis of the user's observations and analysis of the user's social and individual behavior; **categorization of the time spent** doing different actions (to think, to walk, to look around, etc); and the **classification of the errors made** by the user. An example of use of these parameters of evaluation can be seen in the research developed by Vidal ([Vidal et al. 2003], [Vidal, Amorim and Berthoz 2004], [Vidal and Berthoz 2005]), in which the user draws the path that they thought to have covered.

The metrics to evaluate **the decision-making process** are composed of the use of questionnaires and asking the user to "think aloud" (that is, to say aloud what she is thinking). This method was used by Grammenos [Grammenos et al. 2002] in a study on the use of trails in VEs.

3.2 MultiScale Virtual Environments

Navigation has been gaining an important role in the interaction with VEs. VEs are growing larger in size and carry more details, ranging from buildings with many rooms to cities or countries, making the task of navigating through them more complex [Pierce and Pausch 2004]. With great distances involved, one solution would be to ensure that users travel at greater speeds. But, by doing this, accuracy would be sacrificed.

According to Furnas [Furnas and Bederson 1995], presenting large amounts of information at the same time can cause problems for the interfaces in general, because there is too much to see, making navigation difficult. For more than a decade, researchers have been trying to solve this problem by developing techniques for structuring information in different **levels of scale**. The levels of scale are determined by their semantic content, and they have specific settings for the amount and size of information users will be able to see and interact in a specific place or object. The benefit of allowing users to navigate between different levels of scale is the knowledge they gain about the components of the structure formed by them.

Nevertheless, the understanding of such structures can be complicated. For example, in the world we know, objects range from $10^{-16}m$ (size of the smaller elementary particles) to 10^{26}m (size of the universe). These levels of scale are far from what a human being can directly interact with, which ranges from millimeters ($10^{-3}m$) to tens of meters ($10^{1}m$) [Zhang and Furnas 2005]. This fact makes it difficult or even impossible to observe and understand these different levels of scale, and also to interact directly with many of the existing structures in the real world.

To increase the number of levels of scale that human beings can work, thus changing the range of size a human can directly interact with, it is possible to use the unique features of the VEs to allow users to change their level of scale for interaction. One of the advantages of that is that users can see objects from different positions and scales. Being able to do that can reduce or eliminate occlusion and improve the perception of the space that these objects occupy in the environment. Allowing users to choose between different levels of scale allows them to select the most appropriate level for each task, or even to change the level of scale while doing a task to accomplish it more easily [Wingrave, Haciahmetoglu and Bowman 2006].

Zhang [Zhang and Furnas 2005] highlights the importance of providing the ability to control level of scale for interaction when tasks involve objects of different levels of scale. According to Wartell [Wartell, Ribarsky and Hodges 1999], direct manipulation using a device that allows six degrees of freedom can be difficult with large items. Manipulating an object is easier when users can see the entire object without changing their point of view, and when it is within the reach of users' arms. If it is necessary to get away or change the point of view to see the whole object, none of these characteristics is met.

For these reasons, users need a set of techniques that allow the adjustment of their size and change automatically some navigation parameters, such as users' height in the environment (if there is a floor), the speed in which they travel, what they can reach or see and, if using stereo, the distance between the their eyes.

3.2.1 Applications

The study of MSVEs is important because it has a large number of applications, such as cosmos [Song and Norman 1994], navigation in a whole-planet terrain [Wartell, Ribarsky and Hodges 1999], understanding of chemical experiments in a virtual laboratory [Gervasi et al. 2004], visualization of biological structures [Zhang 2005] and geospatial data [Houtgast, Pfeiffer and Post 2005] and study of anatomy [Kopper et al. 2006]. All these applications can use multiple scales because they can be divided into several levels of scale, grouped and organized in a hierarchical structure.

The cosmos application was proposed by Song [Song and Norman 1994], and was the first in which multiscale data was explored in VE. The hierarchical structure organization is the following: the cosmos is the highest level of scale, where users can see the galaxies, which represent the second level of scale. Once inside a galaxy, users can view the planetary systems, which is the third level of scale, and so on.

The application proposed by Wartell [Wartell, Ribarsky and Hodges 1999] lets users travel in a VE that contains a whole-planet terrain. In this application, users can zoom, pan and rotate their viewpoint of the environment using just a laser pointer. As users change their viewpoint of the environment, the system adjusts users' scale parameters to maintain good stereo imagery and to ensure that the navigation methods work in all scales.

The application developed by Gervasi [Gervasi et al. 2004] has the goal of allowing high school students to develop chemical experiments in a virtual laboratory. The application starts when users enter in the laboratory, in which they can access several rooms where different experiments are conducted. After choosing an experiment, different tasks are given involving interaction with the instruments used in the experiment. Although the author does not highlights the use of levels of scale, this application clearly used two different levels of scale: the human, in which users can interact with the instruments, and molecular, in which students can see the molecular structure resulting from his experiment (Figure 18).

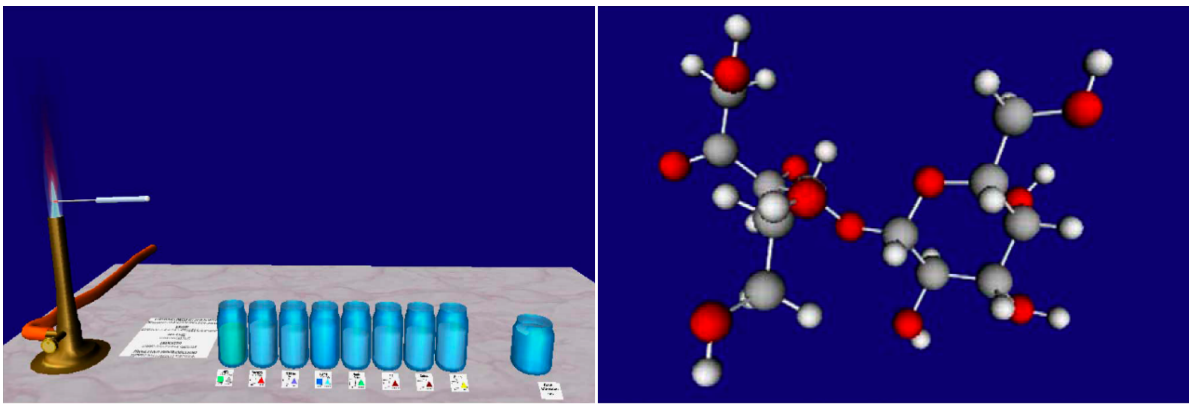

Figure 18: Two levels of scale in the chemical experiments application: human and molecular
Source: [Gervasi et al. 2004].

Zhang [Zhang 2005] has developed an application for visualization of biological structures in which, being at any level of scale, users could choose a new structure they want to observe. The application then shows the atomic relations of the selected structure at different levels of scale, using an animation for the scale transformation as a tool to enhance the perception of the different levels. An example of the different levels of scale in this application can be seen in Figure 19.

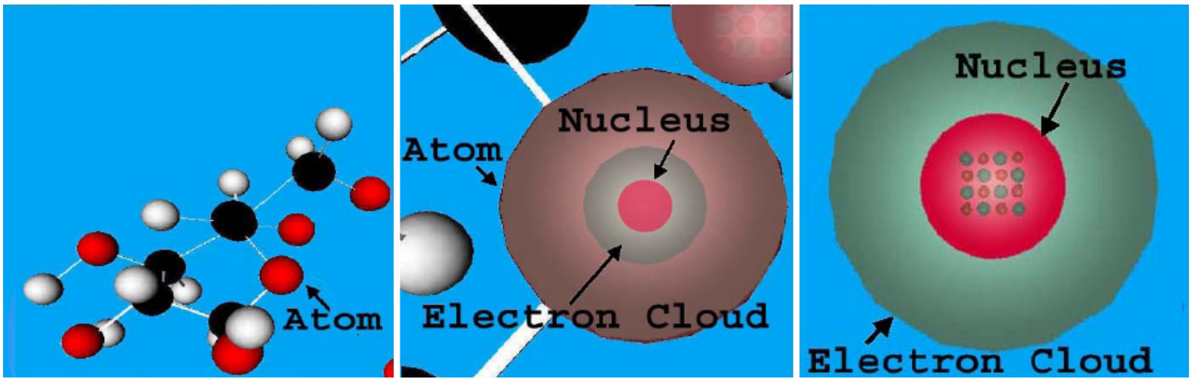

Figure 19: MSVE for visualization of biological structures
Source: [Zhang 2005].

Houtgast [Houtgast, Pfeiffer and Post 2005] implemented an environment for viewing and manipulating geospatial data. In this environment, users can navigate freely through the data volume. To manipulate any object, users have to select them so that they start to travel relative to it. While users are manipulating the object, the system performs a semi-automatic adjustment of their level of scale, position and orientation to allow them to reach and see the entire object.

Kopper [Kopper et al. 2006] has developed an application to test two travel techniques for MSVEs that simulates the study of anatomy. In this application, the levels of scale are the human organs and all objects that are inside of them (e.g.: a tumor inside the right lung). Initially, a virtual human body is in front of the users, and from that, users could select different organs to navigate to. Once inside an organ, they could select tumors, and so on. In the example shown in Figure 20, a user wants to enter in one of the lungs, and uses one of the techniques to indicate that this was the chosen level of scale. This allows, for example, medical students explore the body and have a better understanding of the spatial and hierarchical relationships between organs and the human body.

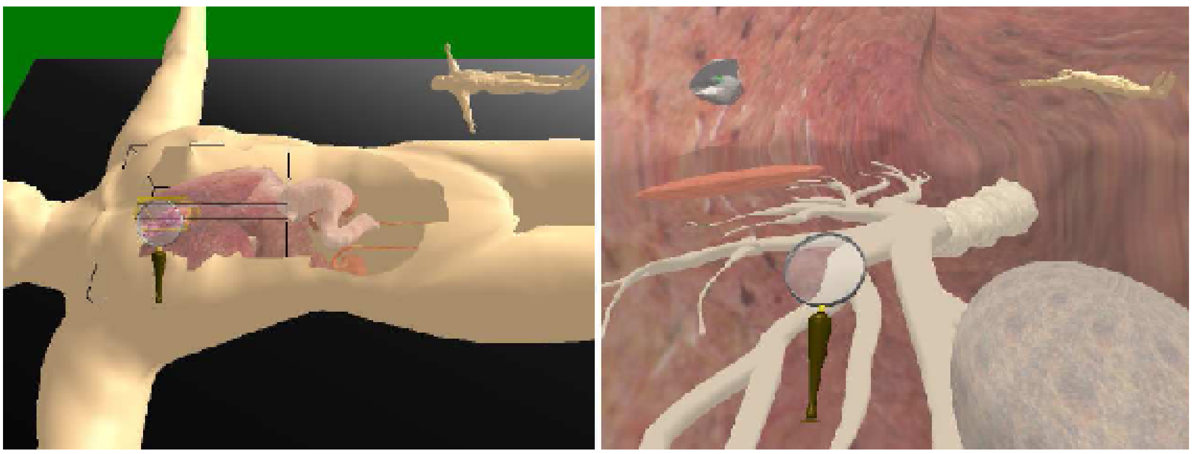

Figure 20: Application for teaching anatomy
Source: [Kopper et al. 2006].

3.2.2 Navigation in MSVEs

A number of travel techniques have indirectly acknowledged that users understand VEs at different levels of scale by providing a handheld miniature version of the world [Stoakley, Conway and Pausch 1995] [LaViola et al. 2001], which may in some cases be scaled up or down [Wingrave, Haciahmetoglu and Bowman 2006]. These tools provide wayfinding cues to the user, but assume that there are only two important levels of scale - overview and detail.

The technique of **pointing to the desired level of scale**, developed by Song [Song and Norman 1994] in its application to travel in the cosmos, uses concepts already familiar to users of 2D interfaces. With the hand, users indicate what level of scale they want to travel to, and travel automatically to the selected level of scale. In order to assist the selection of a level of scale, the system highlights the level of scale the user is touching.

The **World-in-Miniature (WIM)** technique, designed by Stoakley [Stoakley, Conway and Pausch 1995], uses more than one level of scale of the environment for interaction. Unlike the applications described in the previous section, the environment itself does not contain different levels of scale, but the technique is composed of a representation of the virtual world in a higher level of scale, as seen in Figure 21. The miniature of the environment is within the user's reach, attached to one of her hands, enabling the user to use the WIM to select and manipulate objects, in addition to her own representation. These characteristics diminish problems such as occlusion and facilitate the manipulation of larger objects, since all the objects are within the reach of the user for direct manipulation.

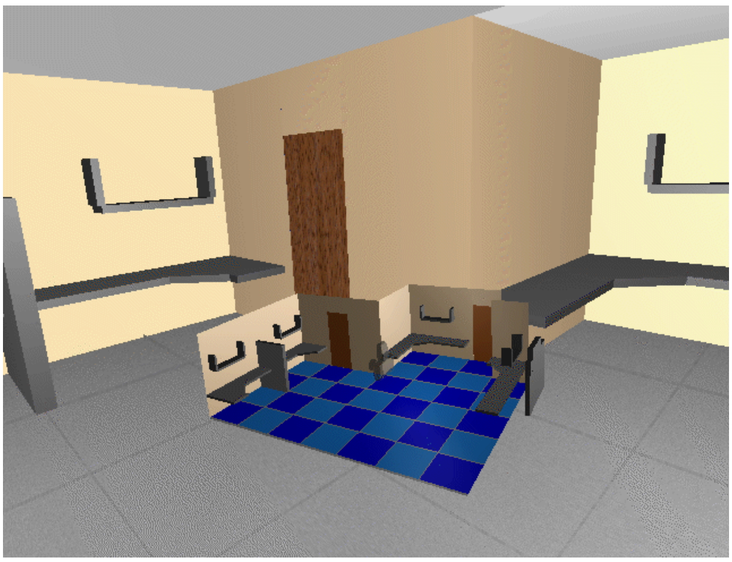

Figure 21: The WIM technique, which allows users to any object or even themselves in a miniature
Source: [Stoakley, Conway and Pausch 1995].

The WIM technique can be rather complex, as the user has to use her hands to carry out the selection, manipulation and navigation tasks. In order to facilitate interaction and to offload some of the work from the hands, Laviola [LaViola et al. 2001] developed a variation of the technique, called **Step WIM**. The idea is to use the user's body for navigation: users can navigate through a WIM found under their feet and tilt their body in the direction they want to go.

The technique **Scaled Scrolling WIM (SSWIM)** [Wingrave, Haciahmetoglu and Bowman 2006] proposes to solve another problem in the implementation of the WIM, which This makes it concerns the size of the environment. This variation of the WIM technique allows the user to change the scale of the WIM, and also scroll to change what portion of the environment she is viewing, making it possible to use the technique in large-scale environments such as big cities.

The travel technique **Seven League Boots** [Interrante, Ries and Anderson 2007] is an alternative to methods for indirect travel that uses variable scaling of the user movement. From the detection of the direction of motion that users will do, their scale is increased. This technique solves the problem of the lack of physical space to navigate using physical locomotion.

The set of techniques for traveling through large-scale VEs **Visible Landmarks** and **Place Representations**, developed by Pierce [Pierce and Pausch 2004], could be applied to MSVEs. Visible landmarks are points of reference that become visible, by having a scale factor applied to them, from any point of the environment and serve as a reference to travel. However, in large scale VEs it may be difficult to keep all landmarks visible without visual clutter. In order to solve this problem, the place representations technique was developed (Figure 22).

Figure 22: Place representations technique, with which users can select a new place to visit in the VE by choosing its representation and travel faster
Source: [Pierce and Pausch 2004].

The technique divides the VE into semantic units represented in a hierarchy and, instead of showing the distant visible landmarks, gives the user a representation of what its semantic unit contains. As an example, the environment used in their experiments was composed of four main locations: a beach, a farm, a city and an amusement park. The root node in the hierarchy represents the whole environment, which contains these and other places. The combination of these two techniques allows users to travel large distances with a small number of commands, but do not provide cues about the hierarchy.

The travel techniques that allow users to travel between different levels of scale, developed by Kopper [Kopper et al. 2006], were based on target selection and steering. In the **target-based** technique, the user uses a magnifying glass metaphor to view and select a level of scale, and she will travel automatically to a pre-defined point inside the selected level of scale. This technique is recommended for when users know where to go and want to reach their goal quickly. With the **steering-based** technique, users have to fly towards to the desired level of scale, and enter into it to be automatically scaled. This technique is recommended for when the time is not an important factor.

Regarding wayfinding aids, Kopper used two techniques commonly used in normal VEs: a **three-dimensional map** containing an You-Are-Here (YAH) marker, shown in Figure 23 by the letter A, and a **compass**, represented as the human body and illustrated in Figure 23 by the letter B. The map is a representation of users' current scale, while the compass indicates the orientation of users relative to the highest level of scale, which is the body. Although the author has implemented the wayfinding aids described, he did not carried out a study on its efficiency.

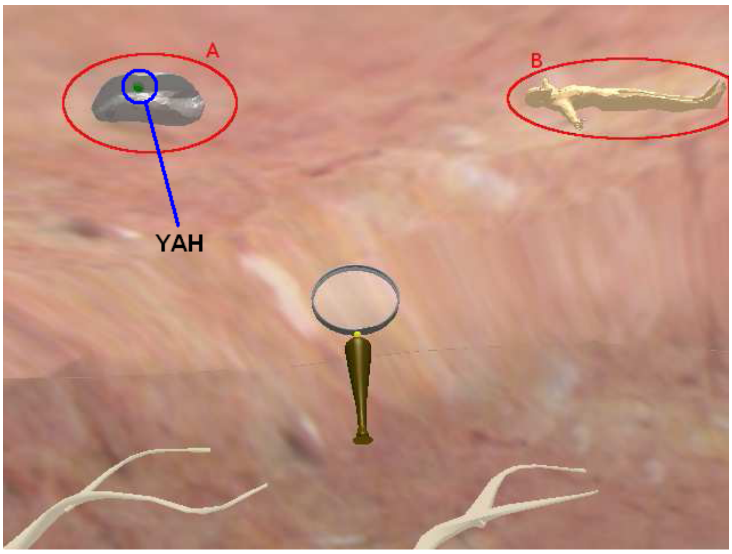

Figure 23: Two wayfinding aid techniques in a MSVE: (A) a three-dimensional map, with a you-are-here marker; and (B) a compass, representing users' orientation relative to the body scale
Source: [Kopper et al. 2006].

Therefore, research is needed to provide better wayfinding aids that allow users to make sense of these complicated environments. Depending on the number of levels of scale in the MSVE, it may be too hard for users to figure how to get from one level of scale to other levels. Thus, it is necessary to understand and classify what kind of wayfinding information users need to travel effectively in this kind of environment.

3.3 Understanding Wayfinding in MSVEs

As shown, there have been only a few travel techniques developed for MSVEs, and none of them concern aiding wayfinding tasks in such VEs. MSVEs applications can be quite big and complicated, and getting lost can be a real problem - even worse than getting lost in a single-scale VE. Although researchers have developed techniques for users to travel through different levels of scales, there is still a need for better wayfinding aids so users can make sense of these complicated environments. For instance, Kopper has implemented some wayfinding aids, described in the previous section, but wayfinding was not the focus of his research and he did not carry out a study on its efficiency. Hence, the focus of this work is on the development of new wayfinding aid techniques, specifically designed for MSVEs. To achieve that, we had to first understand the wayfinding process in MSVEs. We accomplished that through the analysis of the existing applications and techniques to classify and identify the wayfinding information necessary for traveling through different levels of scales without getting lost. Based on the previous work, described in the previous section, we identified two types of wayfinding information necessary to travel in MSVEs: spatial and hierarchical.

Spatial wayfinding information is all wayfinding information that concerns position and orientation of users, objects or specific places in a VE. It can be used to determine distances, landmarks position and directions. In the case of MSVEs, it concerns the levels of scale. This kind of wayfinding information is the basis of most of the existing wayfinding aid techniques, such as the compass [Burigat and Chittaro 2007], signs [Cliburn and Rilea 2008] and maps [Darken and Cevik 1999]. With spatial wayfinding information, it would be possible to determine in which direction to go to get to a specific level of scale, where this level of scale is positioned, and what is the orientation of that level of scale in relation to the user and to other levels of scale. A detailed list of the spatial wayfinding information we identified as required for traveling effectively in MSVEs is presented below, together with a justification of why the information is needed:

- Users' current position in space relative to the highest level of scale to enable them to know their position in the context they are in;

- Users' current position in space relative to their current level of scale to enable them to know where they are in the current level of scale;
- Users' current position in space relative to any other level of scale to enable them to use other levels of scale as landmarks or reference to their position;
- Users' current orientation relative to their current level of scale to enable them to know in which direction they should go to get to the top of their current level of scale;
- Target level of scale position in space relative to the highest level of scale to enable them to know where the level of scale that they wish to visit is, relative to the context in which they are;
- Target level of scale position in space relative to user's current position to enable them to know how to get to their objective;
- Target level of scale position in space relative to other levels of scale to enable them to use other levels of scale as landmarks to get to their objective;
- Target level of scale orientation relative to user's orientation to enable them to know in which direction they should go to get to their objective;
- In addition to this, all the described information is important for users to be able to determine a path to be followed in space to get to the target destination and to build up spatial knowledge about the VE.

Hierarchical wayfinding information is all wayfinding information relative to the hierarchical structure formed by the levels of scale, such as in which levels of scale there is a certain tumor, or in which organ the user is, and so on. It helps users to know and understand the relationships between different levels of scale, independently of their position in space or scale. A detailed list of the hierarchical wayfinding information we identified as required for traveling effectively in MSVEs is presented below, together with a justification of why the information is needed:

- Users' current position in the hierarchy to enable them to know where they are in the context they are in;
- Users' current position in the hierarchy relative to lower levels of scale to enable them to know what levels of scale there are left to explore from their current position;
- Users' current position in the hierarchy relative to higher levels of scale to enable them to know where they will go if they leave their current level of scale;

- Other levels of scale at the same level in the hierarchy to enable them to know where to look for new levels of scale at the same level, or similar levels;
- Target level of scale position in hierarchy to enable them to know where a level of scale is in the hierarchy and how many levels of scale they will have to visit to get there;
- Target level of scale position in hierarchy relative to the lower levels of scale to enable them to know what is nested within their objective;
- Target level of scale position in hierarchy relative to the higher levels of scale to enable them to use higher levels of scale in the hierarchy as landmarks to get to their objective;
- Target level of scale position in hierarchy relative to the other levels of scale at the same hierarchy level to enable them to know where to look for similar levels of scale;
- All this information is important for users to be able to determine by which levels of scale they need to pass to get to the target destination and to be able to build up hierarchical knowledge about the VE.

The difference between these two kinds of information is that hierarchical information is abstract, i.e. it shows that a level of scale is nested in another level of scale, while the spatial information is concrete, i.e it indicates where this level of scale is located inside the other. For instance, if the user is inside the right lung, and decides to go to the left lung, hierarchical information would tell her that she needs to leave the right lung to be in the body scale, and then would need to enter the left lung. In this example, the spatial information would tell her where the left lung is located in the body and in which direction she would have to travel to get there from the right lung.

4 Design and Implementation of Wayfinding Techniques

This chapter presents the design and implementation of wayfinding aid techniques for MSVEs. These techniques were based on the wayfinding information we identified in the previous chapter as needed for traveling effectively in such complicated VEs.

4.1 Research Testbed

The application used for this study is a modified version of that developed by Kopper [Kopper et al. 2006], which simulates the study of anatomy. In the original application, the levels of scale are the human organs and the objects that are inside them. To use this application as our research testbed, some changes were made.

In order to diminish unnecessary cognitive load, the hierarchy and the levels of scale of the original application have been designed to be part of the same context. In the original application, once the user was inside an organ, there were only spheres, and they had no meaning in the context of anatomy. Thus, we defined the following hierarchical structure: organs are nested in the body, tumors are nested in the organs, cells are nested in the tumors, ribosomes and nuclei are nested within the cells, chromosomes are nested in the nuclei and the DNA chains are nested in the chromosomes. All levels can be seen in Figure 24.

Similarly, we also wanted to create a structure that is at the same time big and complex enough in terms of number of levels of scale, so we can understand how users gain and keep spatial and hierarchical knowledge, and at the same time simple, in terms of what users have to learn about it. The hierarchical structure formed by the levels of scale in the original application had little complexity, as there were only 21 different levels of scale to explore. Additionally, the hierarchical structure had no meaning in its context, making the process of learning about it harder. In order to better evaluate the techniques, we created a number of tumors inside the organs, and made all the tumors have one cell. All cells contained the same hierarchical structure within them: the nucleus and ribosomes, the chromosome and the DNA. The resulting structure can be seen in Figure 25.

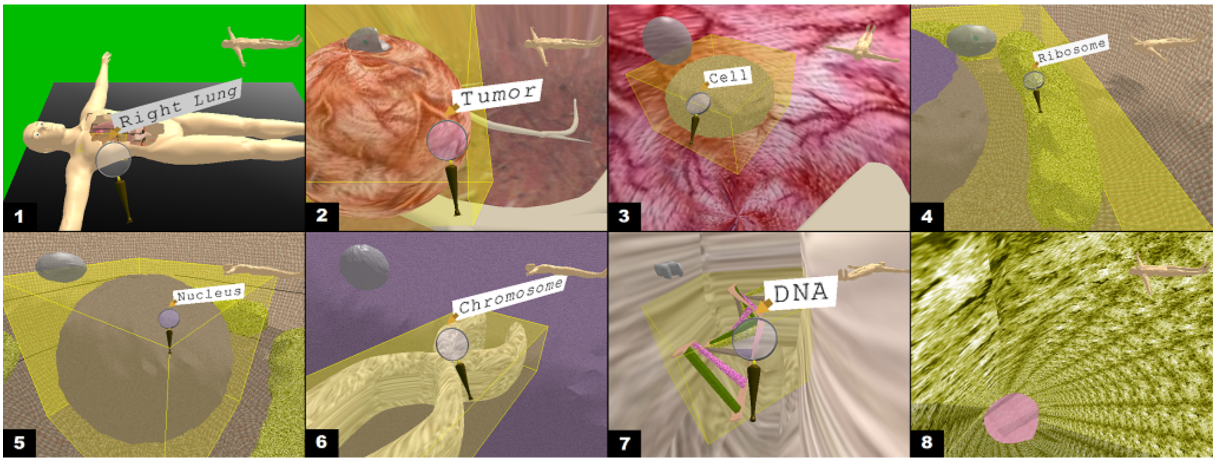

Figure 24: All the levels of scale: human, containing the organs (1); organs, containing tumors (2); tumors, containing a cell (3), cell with ribosomes and a nucleus (4 and 5 respectively); the cell nucleus, containing a chromosome (6); the chromosome, with a DNA chain (7); and finally, the DNA level of scale (8)

The modifications made to the environment was the starting point for the development of the new techniques. We also created a practice world, which is a simplified version of the environment used in the experiment. In this simplified version of the VE, users travel through spheres inside a body.

4.2 Designed Techniques

After defining the wayfinding information needed for navigating in MSVEs, we designed the new navigation techniques using a design technique called scenario-based design [Carroll 1995], which is an iterative model for interface design, based on a problem description. From this problem description, new interaction techniques are designed based on the description of activities performed by the users, information presented by the system and how users interact with this information. The scenario-based design of our techniques is available in Appendix A.

Three different ideas were initially considered and designed, two based on spatial information and the other based on hierarchical information. The first idea was based on spatial information, and is a variation of the WIM, an interactive three-dimensional map of the VE that allows users to view multiple scales. This technique was named **MultiScale World-In-Miniature (MSWIM)**, and is one of the two techniques implemented. The second idea was a two-dimensional map using focus+context techniques, such as fish-eye [Furnas 1986], to view and interact with multiple scales. This technique was discarded during the design phase, as it would be really hard to keep the context visible in smaller

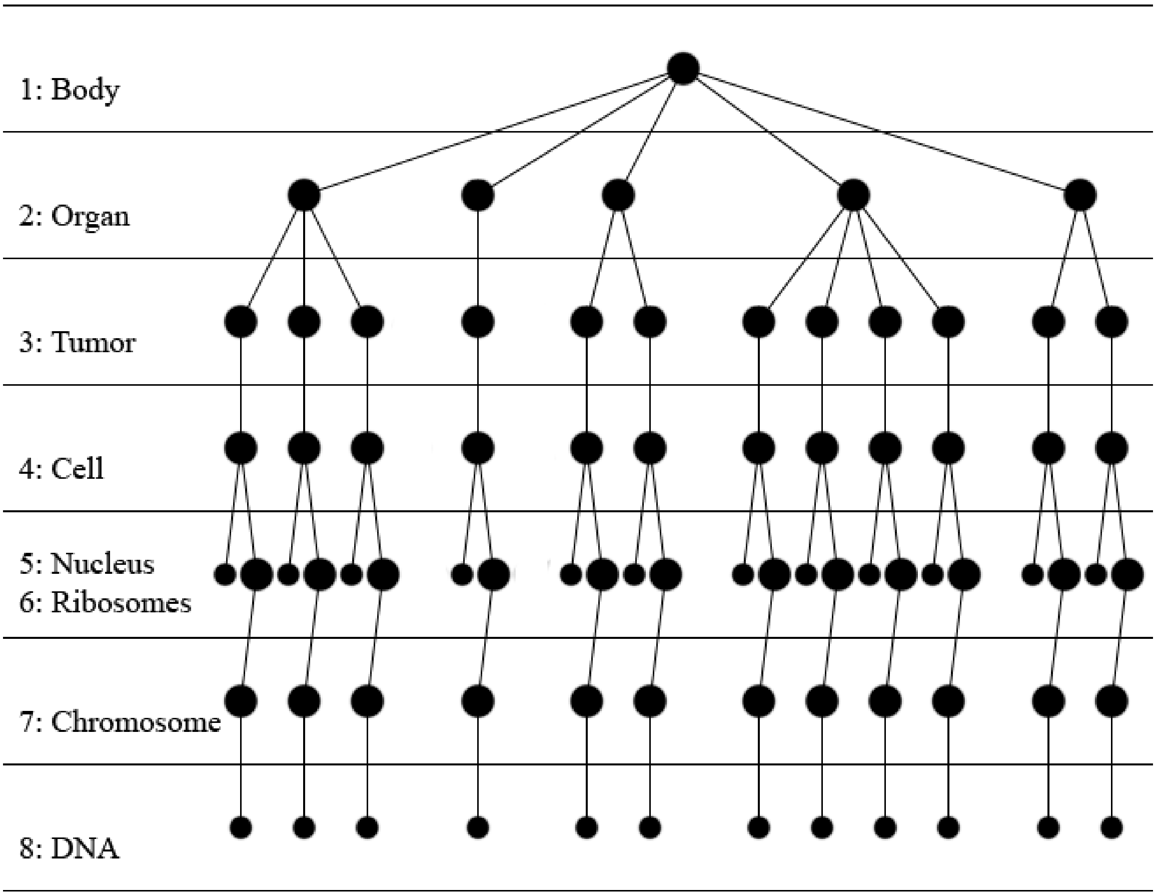

Figure 25: The hierarchical structure formed by the levels of scale, mapped to the levels of scale illustrated by Figure 24

scales. The third idea considered for this work was to present the whole hierarchy to user, in a way that he could view and select any level of scale anytime. This is the second implemented technique, and it is called **Hierarchically-Structured Map (HiSMap)**.

Before describing specific features of each technique, it is important to highlight some of the features shared by them. With both techniques, users have a virtual hand attached to their right hand. The virtual hand is used to interact with and to use the techniques. They also have the possibility of using the steering technique to maneuver within a level of scale, or even enter and leave levels of scale. The compass, described by Kopper, is always provided, independently of the technique used. The developed techniques also use two buttons for interaction: the **selection button**, which allows users to select and deselect levels of scale for interaction; and the **travel button**, which allow users to travel automatically to the selected level of scale.

The hardware requirements for all techniques include a head-tracked HMD, a 6-DOF handheld input device with at least two buttons and a joystick and a handheld tablet tracked in 6-DOF. The tablet worked as a physical prop to a virtual tablet, which displays the technique on top of it. Figure 26 illustrates the complete hardware setup.

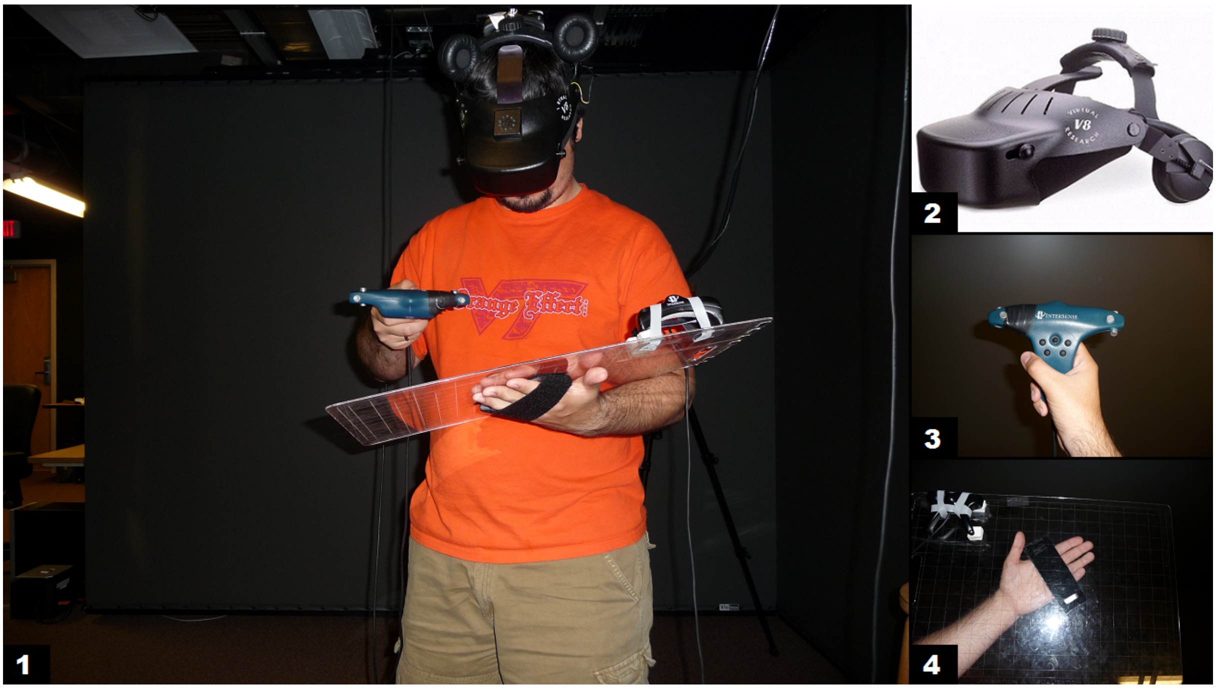

Figure 26: The complete hardware setup (1) used by the developed techniques, composed by a HMD (2), a wand (3) and a handheld tablet (4).

In the next sections, the baseline technique (combination of the existing techniques) and the developed techniques are presented. After, the results of a informal study on the developed technique's usability are shown. Finally, the last section of this chapter illustrates how the techniques can be mapped into the wayfinding information described in Chapter 6.

4.2.1 Baseline Techniques

We combined the travel techniques developed by Kopper, so that users have the ability to quickly change their level of scale with the target-based technique, and also to be able to maneuver and explore new levels of scale using the steering-based technique.

The **target-based technique** uses a magnifying glass metaphor, with which users can investigate their current level of scale and search for new levels of scale to explore. When looking at levels of scale through the magnifying glass, a yellow box highlights the object that is nearer to the center of the glass, and black wireframe boxes highlight the other visible levels of scale. The one highlighted by the yellow box is the one that is selected for interaction. Users can press a button to automatically travel to that level of scale, or press another button the get out of their current level of scale. As soon as they enter or leave a level of scale, their interaction parameters are automatically adjusted.

The **steering-based technique** uses a virtual hand and a joystick to allow users to navigate relative to their hand orientation. For example, if the user points up and press the joystick up, she will go up; but if she presses the joystick down, she will go down. The same applies for when the user is pointing forward - if she presses the joystick up, she will go forward; and if she presses the joystick down, she will go backward. It is possible to use this technique to enter and leave levels of scale as well. To do it, the users have to enter the level of scale using their hand and the joystick to travel, and, when inside a new level of scale, they just have to stop pressing the joystick. Once they do, they will be automatically scaled up or down.

To combine the two techniques, we used the magnifying glass to view and select levels of scale with the target technique, and as a substitute of the virtual hand. In addition, an important feature was added to the magnifying glass to help users build spatial knowledge: a text describing the scale that has been selected for interaction. Whenever the magnifying glass is being used to view the levels of scale that could be selected, the text description appears attached to it, as in Figure 27.

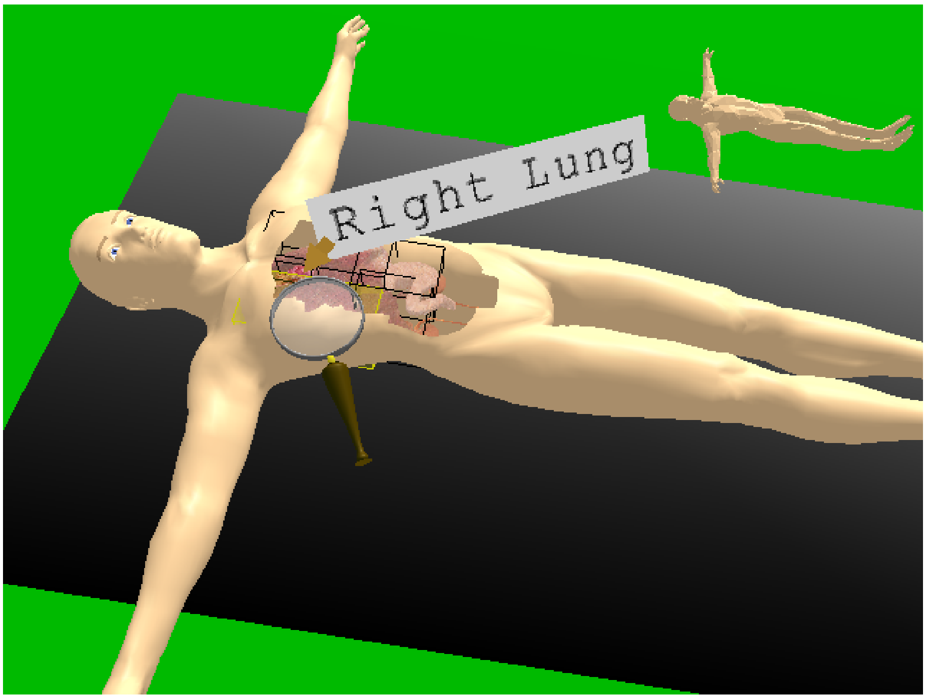

Figure 27: The level of scale “Right Lung” being highlighted with the baseline technique: a combination of the target-based and steering-based techniques [Kopper et al. 2006].

4.2.2 MSWIM Technique

The MSWIM technique is based on spatial wayfinding information and was inspired by the Scaled Scrolling WIM [Wingrave, Haciahmetoglu and Bowman 2006], a modified version of the original WIM technique that allows users to zoom and pan what they are seeing in miniature. We extend this idea to our MSWIM technique by adding explicit support for hierarchies of scale. With the MSWIM, users view and select levels of scale to easily travel between different levels of scale, determine spatial position of specific objects, distance between objects, orientation, etc. However, in the MSWIM, users can view the objects in the world, but cannot manipulate them. Also, there is no user representation in the miniature.

The MSWIM is located inside a box over the virtual tablet, and the selected scale for interaction always appears as a translucent object, as shown in Figure 28. Levels of scale that are at the same level of the hierarchy or are inside the selected one are opaque and selectable.

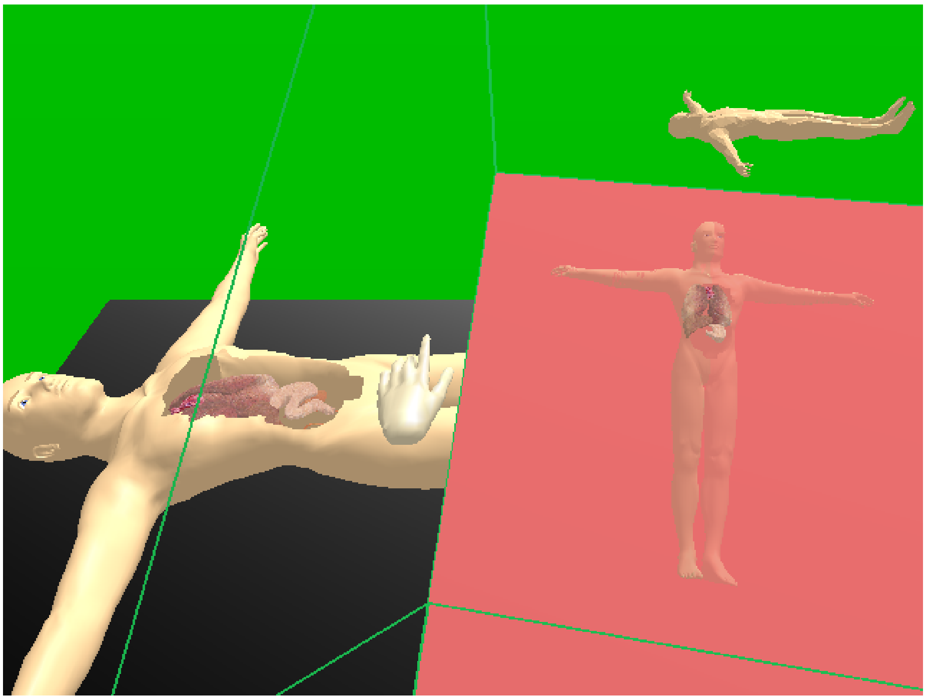

Figure 28: The virtual hand and the virtual tablet with the MSWIM technique being displayed on top of it.

As the virtual hand touches the levels of scale inside the body, a red box highlights the scale they are touching and a text appears attached to it describing what the scale is. In addition, as users touch the levels of scale, not only does its miniature becomes highlighted, but the object that represents the level of scale becomes highlighted as well (Figure 29).

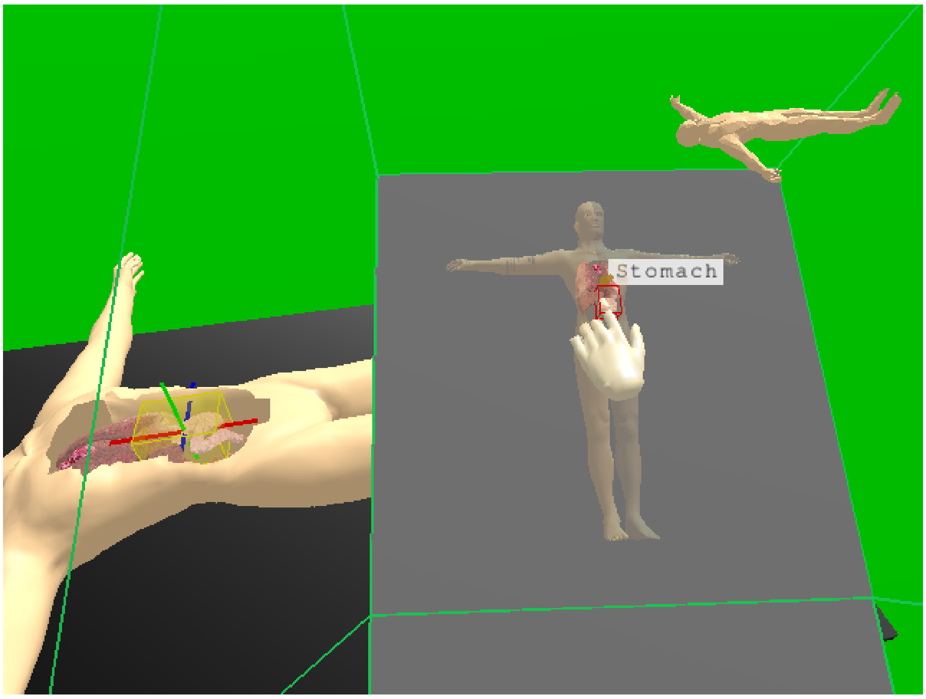

Figure 29: The virtual hand touching the level of scale "Stomach" in the MSWIM technique; the level of scale and its miniature become highlighted.

To change the selected level of scale for interaction in the MSWIM, users have to press the selection button when touching a level of scale. Then, the selected level of scale increases in size and becomes translucent so that users can see and interact with levels of scale inside the one they have selected. The process of changing the level of scale for interaction is animated to enable users to have a better understanding of the context in which the selected scale is. To go back to the previous level of scale, users just have to press the selection button when not touching anything with the virtual hand. It is also possible to pan and change the portion of the selected level of scale that will be seen in the box.

To travel using this technique, users select the level of scale to which they want to travel and press the travel button. Once the button is pressed, the MSWIM disappears and user start traveling to the selected scale. Figure 30 shows an example of how this happens when a cell is selected for travel.

When traveling, the path to get to the selected destination appears on the left side of the screen, and a blinking red arrow indicates the direction of travel: from the body to the right lung, and from the right lung to the white tumor. In addition to this, the current level of scale always appears in the center of the screen; hence the path is scrolling up in Figure 30.

If the user selects a higher level of scale in the WIM, the scale in which the user is becomes highlighted. Also, three lines crossing each other inside it show the user's current position. When the selected level of scale is not the entire body, a little body appears attached to the lower left portion of the WIM. This gives reference to where the user is within the body.

Also, if the selected scale in the WIM is not the same as the users' current scale, two arrows appear. The one attached to the lower left part of the WIM points to the users' current scale, relative to the selected scale in the WIM. The other arrow is attached to the hand, and points to the position in the VE of the selected scale in the MSWIM. Figure 31 shows both arrows and the reference body.

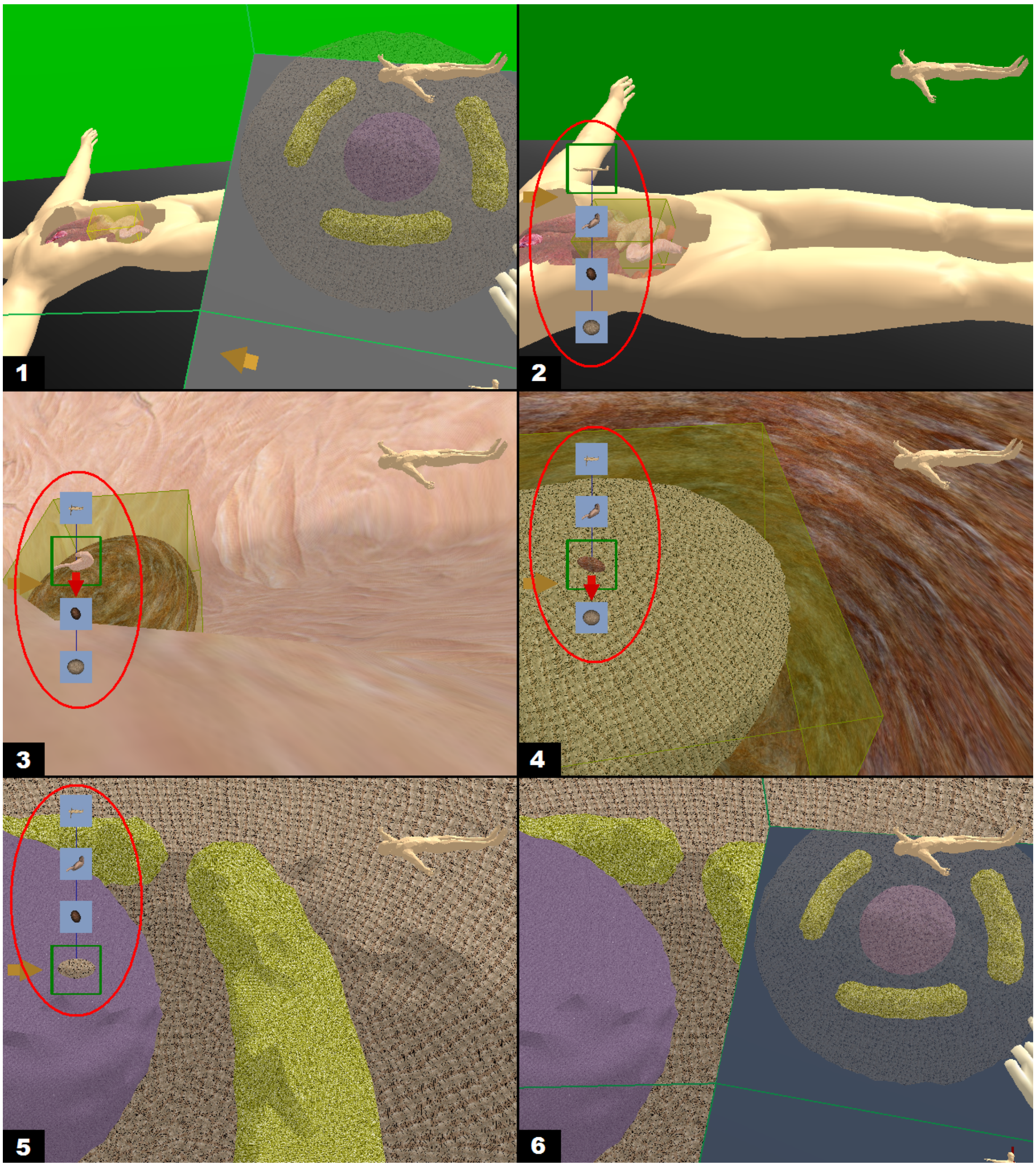

Figure 30: Animation of travel between two different levels of scale showing the user with the cell selected (1), starting to travel (2), passing through the body (3) and the tumor (4), and finally getting into the cell (5 and 6) and the hierarchy path being covered (highlighted in 2, 3, 4 and 5 by a red circle).

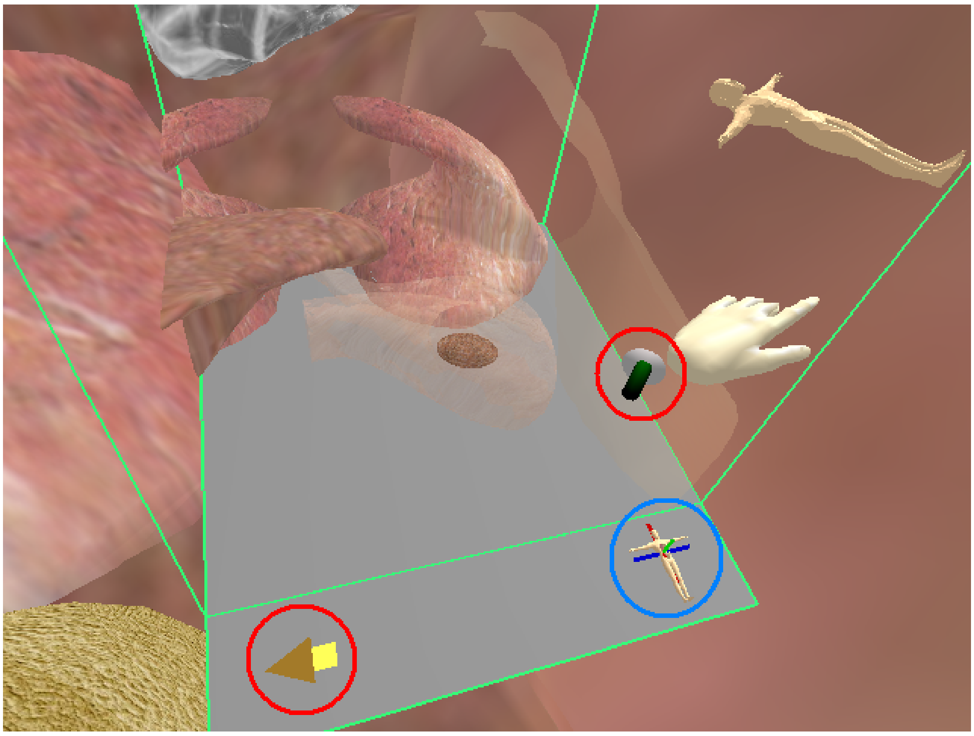

Figure 31: The arrows highlighted by red circles indicate the position in space (green) and the miniature (yellow) of the selected scale in the miniature and the users' current scale, respectively, plus the body highlighted by a blue circle that serves as a reference when the selected scale is not the entire body.

4.2.3 HiSMap Technique

The HiSMap technique is based on hierarchical wayfinding information and was inspired by the technique place representations, which divides large-scale VEs into semantical units, organized in a hierarchical structure, to allow the user to quickly navigate to distant places. We extend this idea in our HiSMap technique by providing representations of all levels of scale, as well as the hierarchy formed by them, so that users can view and select any level of scale at anytime. Figure 32 shows this idea implemented, with several icons connected by blue lines over the virtual tablet. Each icon represents a specific level of scale, and the lines connect nested levels of scale. The rows in which these icons are located represent how many scales nest the level of scale that is illustrated by the icon.

If the user moves the virtual hand and touches the icons, the selected scale changes to the one that is being touched. In Figure 33, the ribosome is the selected scale, so it is represented by its 3D model. As the icon is touched, it becomes bigger than the other icons. Also, not only does it become highlighted, but the organ where the icon is becomes highlighted as well. Whenever the user is not touching or do not have a level of scale selected, her current level of scale in the hierarchy will be the selected scale.

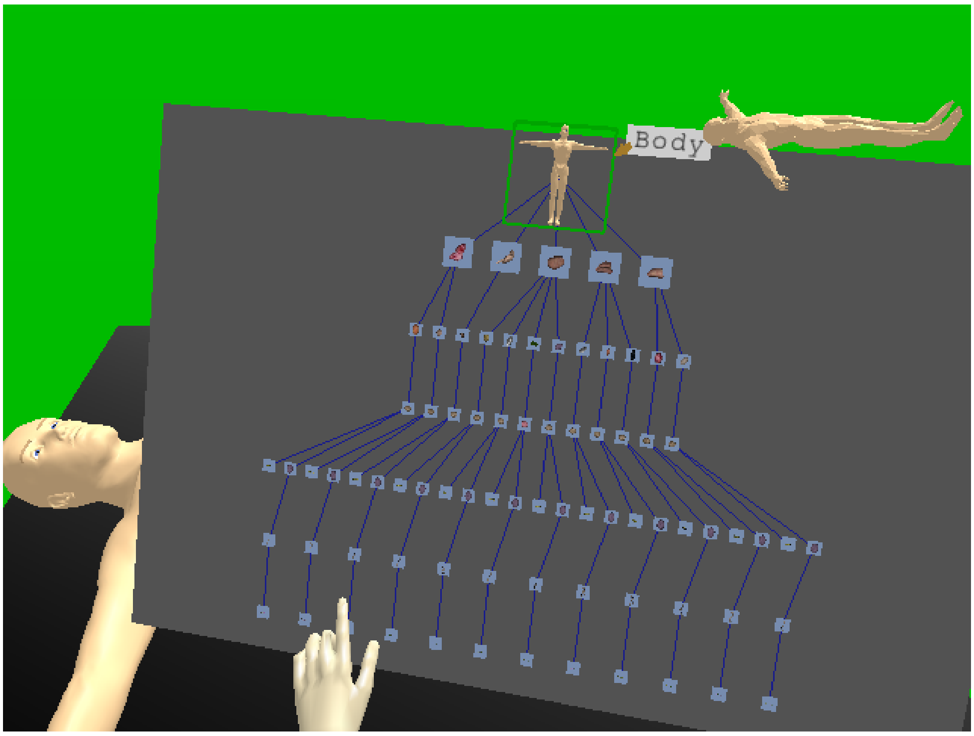

Figure 32: The HiSMap technique, which shows the whole hierarchy to the user.

In order to keep a level of scale selected even when it is not being touched, the user has to press the selection button. Doing this will "freeze" the hierarchy as it is, and the selected scale will not be updated. If the user touch other levels of scale in the hierarchy to see what they are, they do not grow or turn into 3D models, but a red box highlights them and their text description is attached to them. This helps users when they have to focus on a specific level of scale in the hierarchy.

Figure 33 shows the body turned into an icon and the line that connected the body to the selected scale turned red. This means that the body is on the path to be followed to get to the selected scale. In addition to this, a red arrow blinking appears right above the body icon. This arrow indicates that the body is the users' current position in the hierarchy.

To travel using this technique, users just have to select the scale to which they want to travel to and press the travel button. Once the button is pressed, the tablet disappears and users start traveling to the selected scale, just like with the MSWIM technique.

4.2.4 Informal Usability Study

An informal usability study was performed using the MSWIM and HiSMap techniques.. Users were presented with the practice environment, so that they could learn all

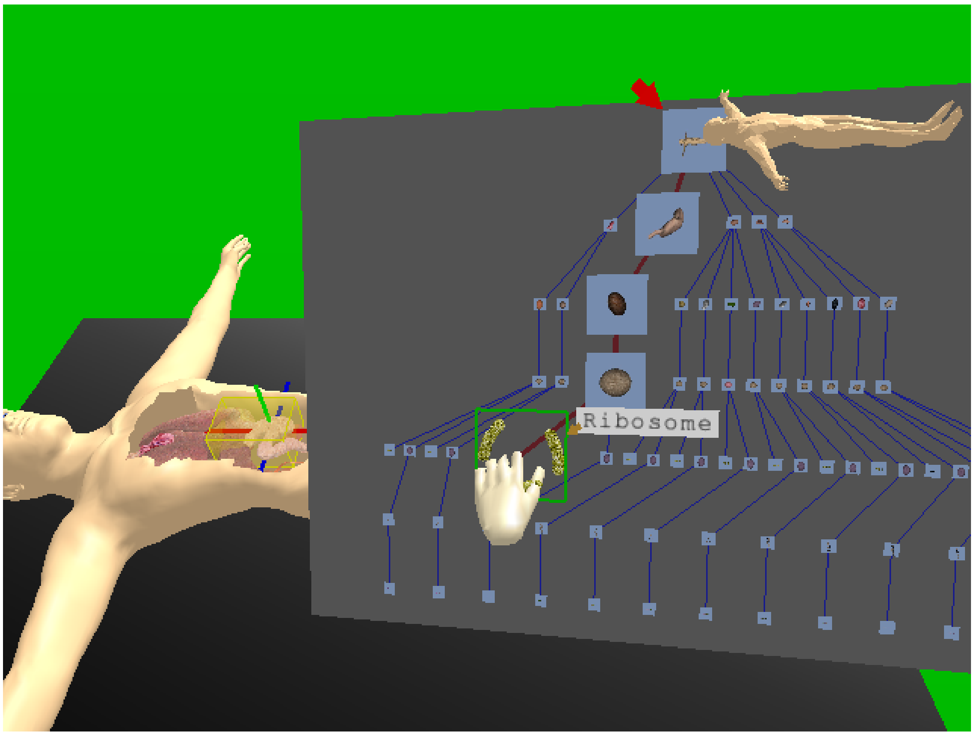

Figure 33: The level of scale and its icon representation being highlighted when touched.

about the technique they would be using. After practicing, they performed some simple navigation tasks that required them to use all existing features from both techniques. Four subjects participated in the informal usability study, three experienced with VR and multiscale applications and one with no experience at all. The following problems were found, together with suggestions made to solve them and what we decided to do:

- **Problem:** the joystick was too sensitive; it was really hard to press the joystick in one specific direction because the interaction resolution of the joystick is too big. **Solution:** decrease the interaction resolution, reducing the number of directions processed for the steering technique and the scrolling in the MSWIM to eight: up, up-right, right, down-right, down, down-left, left and up-left;

- **Problem:** to be automatically scaled when using the steering technique, it was necessary to stop pressing the joystick. **Suggestion:** always do automatic scaling with the steering technique, and not only if the subject stop pressing the joystick. **Why it was not implemented:** Kopper tried to do this in his study, and it did not work out better;

- **Problem:** it may be more counter-intuitive to use one button to zoom in and the same to zoom out with the MSWIM. **Suggestion:** use two buttons, one for zooming in and one for zooming out. **Why it was not implemented:** having two different buttons schemes for the techniques can make it difficult to use them combined;

- **Problem:** subjects reported some difficulty to select small objects on the MSWIM, mainly because of registering problems with the virtual hand, known as Heisenberg effect [Bowman et al. 2001]. **Solution:** the level of scale is only selected when the selection button is released;

- **Problem:** in the first version of the MSWIM technique, scrolling could be used to change the selected scale. The level of scale that was nearest to the center of the tablet was going to be the new selected scale. If there was no scale near to the center of the tablet, the selected scale would be the higher. But, because users have to point in the right direction and wait until it gets to the middle of the WIM, it was not being used. Also, its functioning was too confusing. **Solution:** scrolling does not change the selected scale anymore. Also, the scrolling is a little bit faster;

- **Problem:** it is difficult to have an idea of how deep the user is in the hierarchy with the MSWIM and hard to keep spatial references with the HiSMap. **Suggestion:** make the hierarchy tree map that is shown when the user is traveling visible all the time with the MSWIM and show the reference body with the HiSMap. **Why it was not implemented:** we wanted to keep the types of information separate by their techniques, so that we can compare how users use different types of information, and what is more efficient for this kind of environment;

- **Problem:** in the initial version of the HiSMap technique, the arrow that indicated the user's position in the hierarchy was hard to notice, because of its color (yellow) and size. **Solution:** we made it bigger, and changed its color to red.

4.2.5 Wayfinding Information

Table 1 describes the spatial and hierarchical information we have assumed as needed for traveling effectively in MSVEs and a summary of the extent of information provided by the designed techniques.

Table 1: Table describing the identified wayfinding information and the amount of wayfinding information each technique provides.

<table>
<thead>
<tr><th>Type</th><th>Provided information</th><th>Baseline Techniques</th><th>HiSMap</th><th>MSWIM</th></tr>
</thead>
<tbody>
<tr><td rowspan="8">Spatial</td><td>Current position relative to the top level of scale</td><td rowspan="8">Moderate-quality information about position in current level of scale and orientation relative to the world; no information about other aspects</td><td rowspan="8">Moderate-quality about most spatial aspects</td><td rowspan="8">High-quality information about all spatial aspects</td></tr>
<tr><td>Current position relative to the current level of scale</td></tr>
<tr><td>Current position relative to other level of scale</td></tr>
<tr><td>Orientation relative to the top level of scale</td></tr>
<tr><td>Target level of scale position relative to the top level of scale</td></tr>
<tr><td>Target level of scale position relative to the current level of scale</td></tr>
<tr><td>Target level of scale position relative to other level of scale</td></tr>
<tr><td>Target level of scale orientation</td></tr>
<tr><td rowspan="8">Hierarchical</td><td>Current position</td><td rowspan="8">No information provided</td><td rowspan="8">High-quality information about all hierarchical aspects</td><td rowspan="8">Moderate- to high-quality about most hierarchical aspects</td></tr>
<tr><td>Current position relative to lower level of scale</td></tr>
<tr><td>Current position relative to higher level of scale</td></tr>
<tr><td>Other level of scale at the same hierarchical level</td></tr>
<tr><td>Target level of scale position</td></tr>
<tr><td>Target level of scale position relative to lower levels of scale</td></tr>
<tr><td>Target level of scale position relative to higher levels of scale</td></tr>
<tr><td>Target level of scale position relative to others at the same level</td></tr>
</tbody>
</table>

5 User Study

To evaluate the usability and performance of the techniques we designed, we carried out an experiment. The goal of this experiment was to compare the developed techniques to the combined version of the existing technique using user performance data. We wished to investigate whether users could make use of the spatial and hierarchical wayfinding information provided by our techniques to navigate efficiently through an MSVE, and to verify the various types of information needed for different wayfinding tasks.

The following hypotheses were made:

H1) providing spatial information helps users improve performance in spatial orientation tasks;

H2) providing hierarchical information helps users perform better on naïve search tasks, as users just have to search for a specific level of scale in one hierarchical level;

H3) providing both hierarchical and spatial information helps users build up more survey knowledge.

5.1 Experimental Design

We adopted a four conditions between-subjects design. In this work, we denote the four conditions as Target+Steering, HiSMap, MSWIM and HiSMap+MSWIM.

In the Target+Steering condition, users only have access to the baseline techniques. This is the control group, where little to no spatial or hierarchical information is provided. In the HiSMap condition, users can only use the HiSMap technique. In the MSWIM condition, users can only use the MSWIM technique. The HiSMap+MSWIM condition is the one in which the HiSMap and the MSWIM techniques are combined. Users can quickly change between one and the other, by just pressing a button.

Participants performed five different types of tasks, each representing one kind of information identified and provided by our techniques. Tasks required the use of spatial and hierarchical information, and concerned the hypotheses made. We designed three tasks for each type, leading to fifteen trials. Participants completed the trials in the same order, independently of the condition. The task types are described in Table 2, together with what was measured with them, an example and which hypotheses they tested.

Table 2: Description of the within-subjects variable task types with the hypothesis tested by them, what was measured and examples.

Type	Hypothesis tested	What is being measured	Example
Relative position: determine position relative to organs	H1	Landmark information and knowledge relative to organs	*Tell me if you are closer to the liver or to the heart*
Steering: use the steering technique to go to another scale at the same level	H1	Capacity to determine the path to reach another level of scale at the same hierarchical level	*Use the steering technique (and do not use the travel button) to go to the red cell*
Naïve search: search for a specific level of scale	H2	Hierarchical and spatial information about the level of scale	*Find the level of scale labeled as abnormal cell and travel there*
Comparison: compare levels of scale at the same hierarchical level	H2	Knowledge about current position in the hierarchy	*Compare the abnormal cell with a normal cell and tell me what is the difference*
Knowledge: use of the spatial knowledge acquired (without the techniques and the devices)	H3	Survey knowledge	*Say in which of the organs you were, when you were inside the abnormal cell, and through which levels of scale you would pass to get there again*

The time spent, total distance traveled using the steering technique and the visited levels of scale were the dependent variables for the first four tasks. The errors made were considered as dependent variable for the fifth task type. In the case of the number of visited levels of scale, we considered all the levels of scale that users passed through to complete the task. That is because users in the Target+Steering always had to explicitly select levels of scale (either using target or steering techniques) to get to the one they wanted.

5.2 Apparatus

Throughout our experiment, a Macbook Pro with an nVidia geForce 8600gt graphics card was used, running Mac OS X. The application and the techniques were developed using C++ with the library SmallVR [Pinho 2002] for scene graph operations and OpenGL for rendering. A Virtual ResearchV8 head-mounted display with 640x480 resolution for each eye and a 60-degree diagonal FOV was used for visualization of the virtual world, and its position was tracked using an Intersense IS-900 6DOF tracker. A handheld tablet was used as a physical prop to the virtual tablet, and its position and orientation was also tracked. The tablet was designed to be held by the left hand, so only right-handed people could participate in our formal study. The device that contains the buttons and the joystick is a wand, and it is mapped to the virtual hand. The wand was used to interact with the techniques.

5.3 Procedure

Firstly, before participating in the experiment, users watched a video explaining how the technique they would use works. Before they began the experiment, users were asked to confirm if they were right handed, to read the informed consent form and to fill out a background survey questionnaire, available in Appendix B.

The first part of the experiment was a practice session, in which users were guided through all the features of the techniques they were using. The next step corresponded to the experiment, which consisted of fifteen trials. After finishing a trial, users were asked to rate the ease of accomplishing it. After the completion of a set of tasks, users were given a five-minute break. Upon completion of all sets of tasks, users were interviewed. The exit interview is presented in Appendix B.

5.4 Participants

Subjects were recruited from our university campus. 24 subjects (9 female), aged 20 to 52, participated in the study, 6 participants for each group. All subjects had normal or corrected-to-normal vision and were right-handed. Users were intermediate to experienced computer users, 9 of whom having previous experience with multiscale interfaces and 6 with VR devices and applications. We balanced the groups so that each had at least

2 participants experienced with multiscale interfaces and 1 participant experienced with VR interfaces.

5.5 Results

Results presented in this section are the sum of the performance for the second and third evaluation trials. The performance on the first trial may be used for learning effects analysis in the future.

5.5.1 Time

Figure 34 illustrates the overall results of our experiment in relation to the average task completion time for the naïve search task. This task tests the hypothesis H2, which claims that providing hierarchical information helps users to perform better on naïve search tasks. It is clear that the Target+Steering condition resulted in the worst task performance, and the HiSMap condition was the best for the first task.

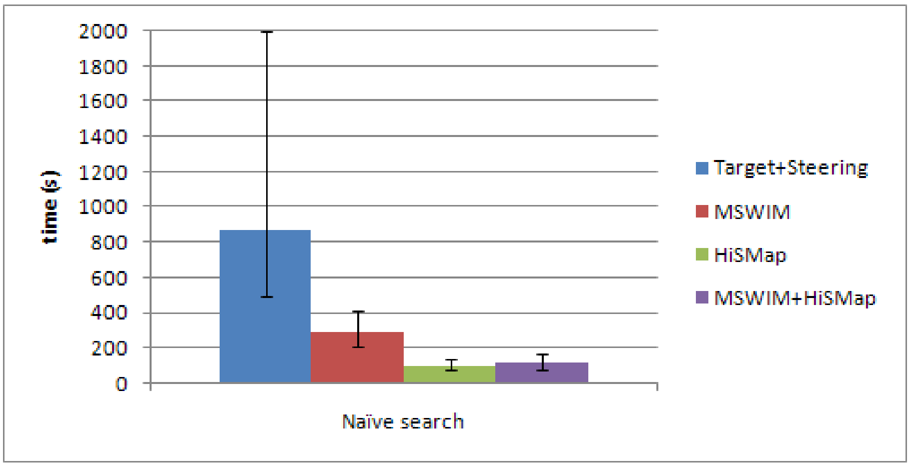

Figure 34: Average time spent for completing the naïve search task.

We performed a one-way ANOVA (alpha-level = 0.05) for all conditions and found a statistically significant effect ($F(3,20) = 9.18$, $p < 0.001$). A post-hoc Tukey HSD test was performed, and significant differences were found between MSWIM and Target+Steering ($p = 0.013$), HiSMap and Target+Steering ($p < 0.0001$), MSWIM+HiSMap and Target+Steering ($p < 0.0001$), MSWIM and HiSMap ($p < 0.001$) and MSWIM and MSWIM+HiSMap ($p < 0.01$) conditions. There was no statistically significant difference between the HiSMap and MSWIM+HiSMap conditions for the first task ($p = 0.764$).

As can be seen in Figure 35, participants in the MSWIM condition spent less time to perform the relative position task. This task tests the hypothesis H1, which claims that providing spatial information helps users improve performance on spatial orientation tasks.

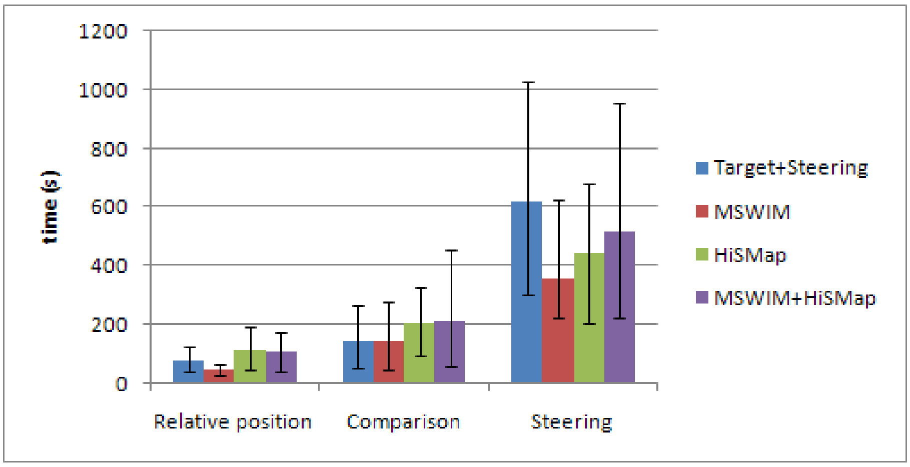

Figure 35: Average time spent for completing the relative position, comparison and steering tasks.

Again, we performed a one-way ANOVA (alpha-level = 0.05) for this task and found a statistically significant effect (F(3,20) = 3.87, p = 0.025). We also performed a post-hoc Tukey HSD test and found that the MSWIM is statistically better than HiSMap (p = 0.036).

We have not found any statistically significant differences between the conditions for the comparison task, which tests hypothesis H2, and the steering task, which tests hypothesis H1. Figure 35 shows that the means and variances of time spent for all conditions in these tasks were very similar, and does not support hypotheses H1 and H2.

5.5.2 Distance

Figure 36 illustrates the overall results of our experiment with respect to average distance covered using the steering technique for the naïve search and steering tasks. The distance is represented as a unit independent of the level of scale for movement. This means that it does not matter if moving a step forward in a level of scale means moving $10^{-4}m$ or $10^{1}m$, we consider this as one step.

As can be seen, for the naïve search task, Target+Steering condition presented an elevated use of the steering technique. The comparison and relative position tasks were not taken into account, as users tended to have little to no use for the Steering technique

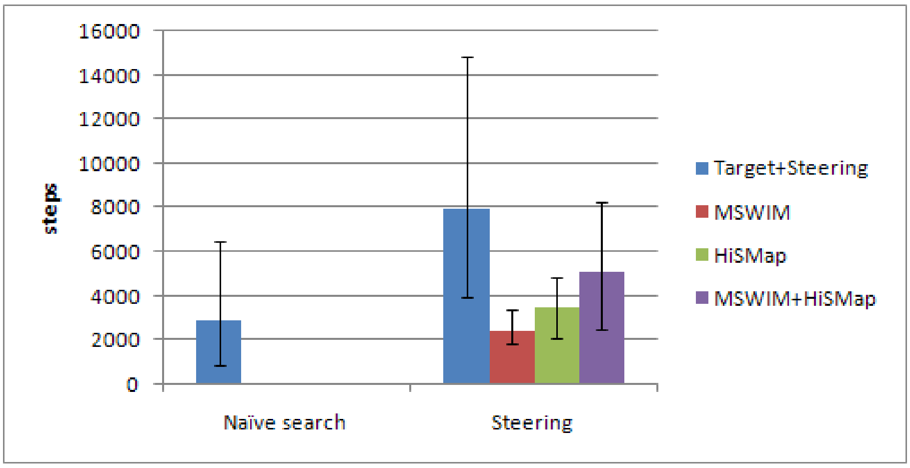

Figure 36: Average distance covered for completing the naïve search and steering tasks.

when performing these tasks.

A one-way ANOVA was performed for the steering task, and we found a statistically significant effect ($F(3,20) = 5.55$, $p = 0.006$). For detecting differences between techniques, we performed a post-hoc Tukey HSD test, and found that participants in the MSWIM ($p = 0.006$) and HiSMap ($p = 0.026$) conditions performed statistically better than those in the Target+Steering condition.

5.5.3 Visited Levels of Scale

Figure 37 illustrates the overall results of our experiment with respect to average levels of scale visited for the naïve search and steering tasks and Figure 38 for relative position and comparison tasks.

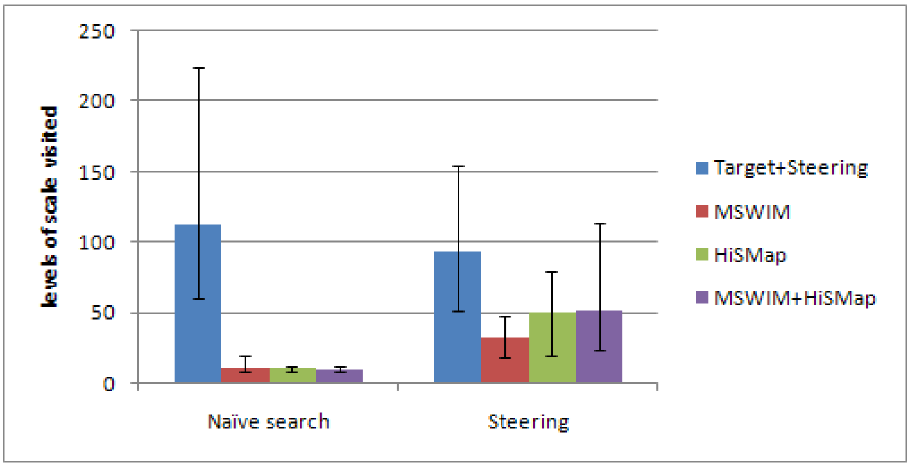

Figure 37: Average number of levels of scale visited for completing the naïve search and steering tasks.

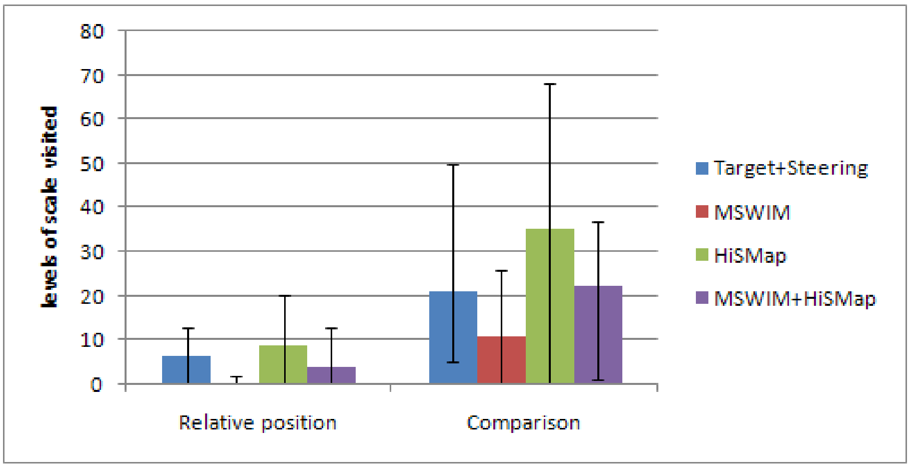

Figure 38: Average number of levels of scale visited for completing the relative position and comparison tasks.

We applied a one-way ANOVA for all conditions and found a statistically significant effect for the naïve search task ($F(3,20) = 17.67$, $p < 0.001$). We also performed a post-hoc Tukey HSD test, and found significant differences between MSWIM and Target+Steering ($p < 0.001$), HiSMap and Target+Steering ($p < 0.001$) and MSWIM+HiSMap and Target+Steering ($p < 0.001$) conditions.

For relative position, comparison and steering tasks, participants in the MSWIM conditions performed better than others. A one-way ANOVA for relative position and steering tasks showed statistically significant effects ($F(3,20) = 3.18$, $p = 0.046$ for the relative position task and $F(3,20) = 4.41$, $p = 0.016$ for the steering task). A post-hoc Tukey HSD test presented differences between HiSMap and MSWIM conditions for the relative position task ($p = 0.035$) and MSWIM and Target+Steering for the steering task. There were no no statistically significant differences between the developed techniques and the Target+Steering conditions in the comparison task.

5.5.4 Number of Errors

Figure 39 shows the results for the knowledge task with respect to the average number of errors. This was the only metric for this task, as the task consisted in giving verbal answers and not in using the techniques or navigating in the MSVE. This task tests hypothesis H3, which claims that providing both spatial and hierarchical information helps users to build up more survey knowledge.

A one-way ANOVA was performed and presented statistically significant differences ($F(3,20) = 4.71$, $p = 0.012$). A post-hoc Tukey HSD test confirmed the differences between

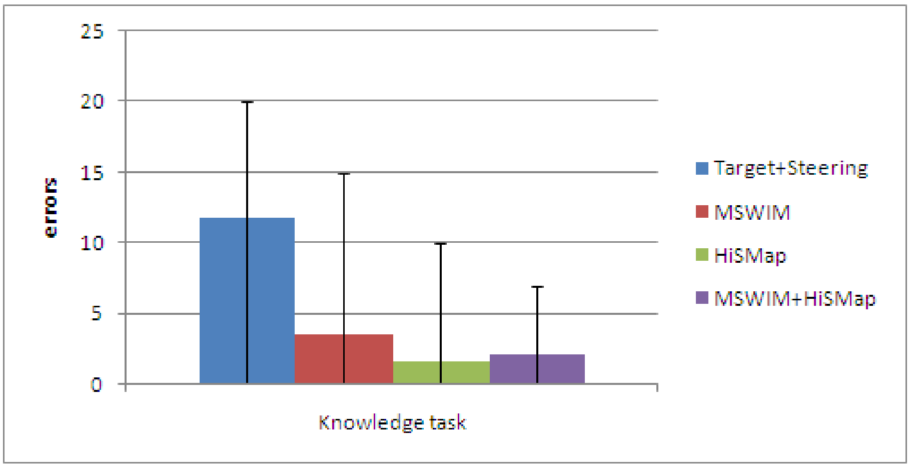

Figure 39: Average number of errors for completing the knowledge task.

HiSMap and Target+Steering ($p = 0.018$) and MSWIM+HiSMap and Target+Steering ($p = 0.026$) conditions. No statistically significant difference was found between the developed techniques.

5.5.5 Subjective Ratings

Figure 40 illustrates the average ratings with respect to subjective ratings of ease of accomplishing the tasks. Ratings range from 1 to 10, and higher ratings are better. For the naïve search task, while the mean rating for the Target+Steering condition was lower than all the others (4.38), the HiSMap condition presented the best results (8.83), not significantly different from the MSWIM+HiSMap condition (8.5). In the relative position task, participants in the MSWIM condition had the best results (8.4). For the comparison and steering tasks, the mean ratings for conditions with the developed techniques had higher scores than the Target+Steering condition.

A Friedman's test was performed to analyze the scores for each task. We found significant changes in scores for the MSWIM ($p < 0.02$) and HiSMap ($p < 0.03$) techniques in regard to the relative position task, with the rating being significantly increased as users repeated the task. Tests for the comparison task showed significant effects for Target+Steering ($p < 0.02$) and MSWIM($p < 0.04$) conditions with an increase in performance. For the steering task, the only condition that presented significant effects on ratings was HiSMap ($p < 0.02$).

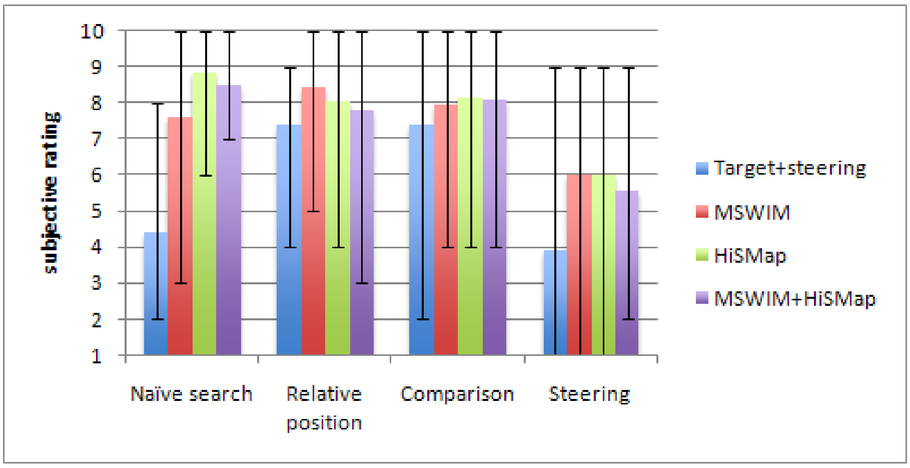

Figure 40: Average subjective ratings for all tasks.

6 Conclusions and Future Work

This chapter presents a detailed discussion on the results of the user study, with the drawn conclusions about each hypothesis. Then, it presents a summary of the contributions of this work. Finally, the future works are presented.

6.1 Discussion

The discussion presented in this section is organized in subsections that present and discuss the results related to each one of the hypotheses.

6.1.1 Hypothesis H1

The results of the relative position task support hypothesis H1, as users that used the technique that provided spatial information performed much better than all the other conditions. In addition, participants in the MSWIM condition found the task easier to accomplish. Interestingly though, the mean time spent for this task with the HiSMap and MSWIM+HiSMap conditions was greater than the time spent by participants in the Target+Steering. Observing the subjective data and the actions performed by those users, it seems that they spent some time looking for the answer in the HiSMap technique. Only after not finding the answer there, did they start to think about how to approach the task. The fact that this happened even when users had the possibility of using the MSWIM technique may be because the HiSMap technique has a lot less components and amount of cognitive effort involved.

Interesting to notice that participants in the MSWIM condition performed much better than the control condition, even though they had to use the same strategy. This could be either because the animation in the MSWIM technique took less time to go from one scale to the other, or because not changing the level of scale for interaction helps users by offloading some of the cognitive effort. To find out if this is true, we performed an analysis on the number of levels of scale selected using the MSWIM technique, and compared to the levels of scale visited by participants in the Target+Steering technique, illustrated by Figure 41.

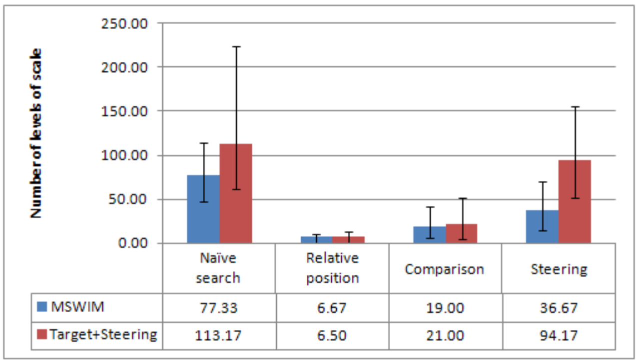

Figure 41: Average number of levels of scale selected with the MSWIM and the Target+Steering techniques.

As can be seen, the averages for both naïve search and steering are different, and participants in the MSWIM condition had to look into less levels of scale than those in Target+Steering condition. A one-way ANOVA was performed to compare them, and we found significant differences for the fourth task ($F(1,10) = 8.31$, $p = 0.016$). This means that changing the actual user scale had an effect on how many scales she will have to visit to find the one that the user is looking for. This may seem strange, but looking at the list of visited scales of participants in Target+Steering and MSWIM condition, we noticed the ones in Target+Steering seemed to forget the levels of scale they had already checked, entering the same levels of scale several times.

For the steering task, the distance covered plays the most important role, as the task is all about using the steering to get to a specific level of scale. In this task, as expected, the MSWIM condition did better than others, mainly because it provides spatial localization information, and not just abstract information like in the HiSMap condition. Interestingly, participants in the MSWIM+HiSMap condition did not perform as well as when they were utilized separately and presented no statistically significant effects on the distance covered by users. We think this happened because of the high cognitive effort needed for learning and using both techniques at the same time. The results for the number of visited levels of scale were similar, being MSWIM the only condition with statistically better results than Target+Steering. Results for the subjective ratings show no significant differences between the conditions with the developed techniques. This also supports the hypothesis H1.

As shown, hypothesis H1, which says that providing spatial information helps users improve performance in spatial orientation tasks, could be confirmed.

6.1.2 Hypothesis H2

The results for the naïve search task support hypothesis H2, because participants that had hierarchical information performed significantly better than those who had not. The time spent by participants in the HiSMap condition for doing the naïve task was much less than with the control condition, while not having to move at all. The number of levels of scale visited for this task was really low and near the ideal number for all conditions except the control one. This was already expected for the HiSMap and MSWIM+HiSMap conditions because the way the techniques were designed allows users to look for the level of scale they desire without changing their current level of scale. Subjective ratings for this task are consistent with the results, as participants in the HiSMap condition presented the best scores. In the Target+Steering condition, participants had to go to every level of scale until they found the one they were looking for.

It is interesting to notice that participants in the MSWIM condition performed much better than the Target+Steering condition, even though they had to use the same strategy. In order to discover why this happened, we performed an analysis on the number of levels of scale selected using the MSWIM technique, and compared this to the levels of scale visited by participants in the Target+Steering technique. The averages for both naïve search and steering tasks are different, and participants in the MSWIM condition had to look into less levels of scale than those in the Target+Steering condition.

A one-way ANOVA was performed to compare them, and we found significant differences for the steering task ($F(1,10) = 8.31$, $p = 0.016$). This means that changing the actual user scale had an effect on how many scales the user would have to visit to find the one that she was looking for. This may seem strange, but looking at the list of visited scales of participants in the Target+Steering and MSWIM conditions, we noticed that participants in the Target+Steering condition seemed to forget the levels of scale they had already checked, entering the same levels of scale several times.

Surprisingly, participants who had only the HiSMap technique performed worse than those in the Target+Steering condition in the relative position and comparison tasks, in terms of visited levels of scale. In the case of the relative position task, this may have happened, as commented by some users, because they expected to have the answer they were looking for in the technique, even after traveling and getting in or out of the level of scale to which they wanted to go or examine. For the comparison task though, only one of the participants in the HiSMap condition had the idea of looking at the 3D model that represented the level of scale in the technique. All participants seemed to avoid using the steering technique in finding the differences in the levels of scale, sometimes going in and out of the same level of scale by selecting it with the HiSMap technique.

The only statistically significant result of the comparison task is that those in the MSWIM condition performed better than those in the HiSMap condition, regarding the number of visited levels of scale. This happened because users in the HiSMap condition just had to find a level of scale in the same hierarchical level, and the path to get to that level was not significant. In the case of the participants in the MSWIM, it was always easier to go by the shortest path, as it would take less time to select the level of scale. Subjective ratings for the conditions with the developed techniques had better scores than Target+Steering, but there were no significant differences between them. Results for this task does not support hypothesis H2.

Hypothesis H2, which says that providing hierarchical information helps users improve performance in naïve search tasks, could be confirmed.

6.1.3 Hypothesis H3

Results for the number of errors in the knowledge task do not support hypothesis H3, as there were no significant differences between the MSWIM+HiSMap and other conditions with the developed techniques. MSWIM, HiSMap and MSWIM+HiSMap conditions presented very similar results, but only participants in the conditions with the HiSMap technique had statistically better results than those in Target+Steering.

Hypothesis H3, which says that providing both types of information could help users to build up more survey knowledge, could not be confirmed.

6.2 Summary

This work presented the conception of wayfinding aids and associated travel techniques, developed specifically for MSVEs. By doing this, we contributed to the research community with the following:

- we identified and classified the wayfinding information needed for traveling effectively in MSVEs;
- we designed two techniques that combine travel and wayfinding aid based on the identified information.

The results of our user study show that the developed techniques perform and provide a better solution for both travel and wayfinding aid. In addition, we also found have found that hierarchical information helps users to perform naïve search tasks better, while spatial information helps users more in spatial localization and orientation tasks.

Another interesting finding is that allowing users to search for a specific level of scale without the need of changing their own scale has positive effects on performance.

Regarding the techniques, one possible limitation of HiSMap is scalability; as the number of levels of scale in the VE increases, the size of the icons representing them decreases. As a consequence, the usability of the technique without some kind of pan and zoom technique would be compromised. The number of levels of scale used in this work was 76, and no study on this matter was carried

The results of this work were published and presented at the IEEE 3DUI 2009 conference as a full paper. The paper is attached in Appendix C.

6.3 Future Work

For future work, we suggest the improvement of the developed techniques based on users' feedback. Some users suggested changes to the techniques, such as the use of explosion techniques for the MSWIM, and use of pan and zoom for the HiSMap, solving the issue of scalability. This would require a new evaluation study, as the complexity of the techniques would increase. An additional evaluation session would be helpful for us, as we would be able to provide users with both techniques and, then, measure satisfaction and other subjective variables.

Another suggestion is to evaluate the effectiveness of the techniques in a different context. In an environment with which users had no familiarity, we would be able to better understand the techniques and how they help users to find their objective.

The wayfinding information used to design our techniques could be used in the development of new interaction techniques for VEs in general. For example, one could use hierarchical wayfinding information and the idea of showing the hierarchy to the user to develop a technique for navigating in large-scale VEs.

Also, an interesting approach would be to combine both spatial and hierarchical wayfinding information in just one single technique. As shown, each of the techniques and the wayfinding information they provide have their strengths, and combining them could mean a better technique. By doing it, hypothesis H3, which says that providing both spatial and hierarchical wayfinding information helps users to build up more survey knowledge, could be tested again.

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Appendix A – Scenario-Based Design

Problem Scenario

John is a medical student, and he will have his first anatomy classes this semester. After doing all the theoretical part of the class, it is time for John to start practicing. However, before actually exploring a real human body, his professor wants try something new, and take the opportunity to increase John's familiarity with the human body structure.
To do this, John's professor wants to use the new the new multi-scale human body simulator. This simulator will allow students to explore the whole body, from the organs to the cells and atoms, and to interact with this whole structure, helping with the whole learning process. When using the simulator, students will have to perform a series of search tasks, involving different organs and parts of the human body structure.
John is a little worried about how to perform the given tasks as he missed some of the theoretical classes. He knows some parts of the human body structure, but, for instance, he doesn't have any idea on how do cells and it's internal parts look like or where they're located in the body structure; he only knows their names. Other problem is that he doesn't know what's inside the heart and the liver, and how they function.
John's professor explains to the medical students that his main goal when using this simulator is to help them build a better understanding of the body structure while searching for abnormalities. Finally, he gives the first task: "you have to find the red cell inside the right lung".
John is curious about how he would get to the red cell using Regis' techniques. He knows, based on his previous readings about the techniques here used, that he will have to travel to a LoS if he wants to know what that LoS have inside. He starts from the whole-body view, and can select/enter into any of the five available organs: right lung, left lung, liver, heart and stomach.
Based on that and on the task's description, he enters the right lung. From now on, he doesn't have a clue on the red cell location. His Task 6ow becomes searching inside each one of the different LoS that are inside the right lung.
When John finds the red cell, he receives his next task: "find the black ribosome inside the liver". John thinks that, if he is close enough of the liver, he may not need to change his scale to get there. However, if he is closer to the heart, he will have to change his scale. The problem is that he is not capable of determining how close he is to the liver or the heart by just looking to the environment around him. To do that, he decides, based on the lack of spatial information provided by Regis' techniques, that he will need to go back to the whole-body view.
After going all the way back to the whole-body view, he tries to estimate the red cell location based on the knowledge acquired while traveling.
After doing that, John's professor tell him to search for a mutant ribosome, that has become black, and is inside the liver. Starting from the whole-body view, John enters the liver. Again, his task becomes to search inside each LoS contained in the liver. As he doesn't know how a ribosome looks like, he will keep searching until he finds a black object.
After finishing all the given search tasks, John's professor ask his students to point the location of the red cell and all other abnormalities inside the body structure. From his current position (he's inside some LoS), John tries to use the compass to estimate the abnormalities positions. To be more certain, he goes back to the whole-body view. From

there, he tries to remember the position of each of the abnormalities that he found, and points out how to get to each one of these abnormalities.
The next task given by John's professor is to list all the levels of scale that he already had visited guided by his professor, and to determine those that are suitable to contain abnormalities and should still be visited. Still in the whole-body view, John has to figure out all the LoS he has already visited and what are the important LoS he hasn't. To do this, he can try to remember by looking into each organ.
Finally, John's last task is to get to the red cell and take a closer look into what is inside of it. John's professor wants him to look how the molecules are formed in a lung tumor and if the DNA is different from the DNA contained in the normal lung tissue.
John goes back to the whole-body view and tries to remember the path to be followed to find the red cell again. He enters the right lung and looks for the tumor that contains the red cell. When inside the right tumor, he looks for the tissue that contains the red cell. When inside the right part of tissue, he looks for the red cell. Once he finds the red cell again, his task becomes to find the DNA and compare it to another DNA contained in a cell that is not in a tumor. To do that, John has to get out of the red cell and the tumor, and find a normal tissue. Once inside the tissue LoS, he looks for the DNA and tries to compare to what he have in his memory.

Activities Scenario

Scale Hierarchy-based Technique

Background…
Task 1 – Finding the red cell
Again, John is curious about how he would get to the red cell using Scale Hierarchy-based techniques. He knows, based on his previous readings about the techniques here used, that he won't have to actually travel to a LoS if he wants to know what that LoS have inside.
He starts from the whole-body view, and has the tablet with the scale-hierarchy in his hand. He then searches for the LoS that looks like a red cell, and select it to travel to it.
Task 2 – Determining which organ is closer
After finding and traveling to the red cell, John has to find out if he is closer to the liver or to the heart. To do that, he looks for his YAH marker in the whole-body LoS represented in the hierarchy. Based on this, he is capable of determining that he is closer to the liver.
Task 3 – Looking for the black ribosome
Using the scale-hierarchy map, John looks for a black object. As he finds one, he uses the stylus to read what is the LoS name, only to find out that the black object he found is a cell, not a ribosome. He then looks for other black objects. When he finds the black ribosome, he selects it to travel.
Task 4 – Pointing the abnormalities
John looks for the abnormalities that he found in the scale-hierarchy map. Except for the abnormalities that are not LoS, he can find all of them without traveling. To determine how to get to the abnormalities and where they are, John only has to look where they are

in the hierarchy tree and the hierarchy path. However, John is not capable to point exactly where they are spatially only looking to the hierarchy.

Task 5 – Listing visited and to-be-visited LoS

To list the LoS that he has already visited, John only has to look for the LoS that contain abnormalities and the ones he selected to travel. To figure what LoS there are still to be visited, he looks for new abnormalities in the scale-hierarchy map.

Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor

John selects the DNA LoS in the map to travel to it. He uses the scales-hierarchy map to look for a normal tissue DNA so he can compare them side-by-side.

Spatial Orientation-based Technique

Background…

Task 1 – Finding the red cell

John is very curious, and he wants to know how he would accomplish all the given tasks with the spatial orientation-based wayfinding aid technique. He also knows, based on his previous readings about this technique, that he won't have to actually travel to a LoS if he wants to know what that LoS have inside.

So, he starts from the whole-body view, and has the SSWIM-like tool attached to his hand. He starts his task by going into the right lung in the SSWIM. Once he is inside, he figures that he will have to select a each LoS in the SSWIM, and look for the red cell just as he was traveling with his normal view. Once he does, he selects it to travel.

Task 2 – Determining which organ is closer

After finding and traveling to the red cell, John has to find out if he is closer to the liver or to the heart. To do that, he zooms out from his current position in the SSWIM and, based on the YAH position, he determines that he is closer to the liver.

Task 3 – Looking for the black ribosome

Using the SSWIM, he gets down on the "levels of zoom" focused on the liver. John looks for a black object. When he finds one, he read its description to see if it is the black ribosome. He keeps going down with the "level of zoom" until he finds he black object that is described as a ribosome and select it to travel.

Task 4 – Pointing the abnormalities

John looks for the abnormalities in the SSWIM focused on the organs and LoS that he already knows as locations for abnormalities, alternating between different "levels of zoom". To determine how to get to the abnormalities and where they are, John has to zoom out in the SSWIM to see his current position and the LoS position.

Task 5 – Listing visited and to-be-visited LoS

To list the LoS that he has already visited, John looks into each of the organs using different "levels of zoom". To figure what LoS there are still to be visited, he looks for new abnormalities in the SSWIM with different "levels of zoom" focused on the LoS he knows he still haven't explored.

Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor

John goes to the DNA "level of zoom" focused on the red cell, and select it to travel. He uses the SSWIM to find another DNA and compare them side-by-side.

2D Top-View Map with Focus+Context Techniques
(very similar to the spatial orientation-based technique)

Background…
Task 1 – Finding the red cell
John has only one more technique to test (he is still curious!), and he wants to know what he would have to do to accomplish all tasks with the 2D top-view map with focus+context wayfinding aid technique. He also knows, based on his previous readings about this technique, that he won't have to travel to a LoS to know what is inside that LoS.
John starts from the whole-body view, and has the 2d map attached to a tablet. He starts his task by zooming into the right lung in the map. Once he does it, he figures that he will have to explore the different levels of zoom focused on the right lung in the map, and look for the red cell. Once he finds it, he selects it to travel.
Task 2 – Determining which organ is closer
After finding and traveling to the red cell, John has to find out if he is closer to the liver or to the heart. To do that, he can either zoom out from his current position and, based on the YAH position, determine that, or he can use the context information contained in the map.
Task 3 – Looking for the black ribosome
Using the map, he goes down on the level of zoom focused on the liver, and looks for a black object. When he finds one, he read its description to see if it is the black ribosome. He keeps going down in the level of zoom until he finds he black object that is described as a ribosome and select it to travel.
Task 4 – Pointing the abnormalities
John looks for the abnormalities in the map focused on the organs and LoS that he already know as locations for abnormalities, alternating between different levels of zoom. To determine how to get to the abnormalities and where they are, John uses the context information contained in the map.
Task 5 – Listing visited and to-be-visited LoS
To list the LoS that he has already visited, John looks into each of the organs using different levels of zoom. To figure what LoS there are still to be visited, he looks for new abnormalities in the map with different levels of zoom focused on the LoS he knows he still haven't explored. He can use the context information to "optimize" this process
Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor
John goes down to the DNA level of zoom focused on the red cell, and select it to travel. He uses the map to find another DNA and can only compare its 2d representation side-by-side. To compare the modified DNA to the 3D representation of the normal DNA, John will have to travel to it.

Information Scenario

Scale Hierarchy-based Technique

Background…
Task 1 – Finding the red cell
John has 2d representations of all the LoS sorted in the tablet in a hierarchical tree. His current LoS is represented as a 3d map that has the same orientation as his. John figures that this is the same as the compass in the original techniques. As he moves around, a blinking dot shows his current position. John also notices that the current LoS is bigger in the map than the others.
He looks for red objects in the map, passing the stylus through it. As he does this, he notices that the stylus position also determine the zoom focus LoS in the tablet. This means that when John is not looking for a particular LoS, the current LoS will be bigger. John also notices that the LoS connected to his selection (or his current position) in the hierarchy tree also get bigger than the other ones, but smaller than the current. Consequently, the LoS connected to the neighbors also get bigger than the other, but smaller than them, and so forth. Also, when the stylus is over a LoS, a text description is shown on the screen. John realizes that he will only have to look for the LoS that is red inside the scales hierarchy map, and that has red cell in its description.
Task 2 – Determining which organ is closer
As John selects the red cell to travel, he notices that the path from the root of the hierarchy tree to the cell becomes highlighted, and he sees the YAH marker in the cell. He figures that he can use the YAH feature combined with the multiple LoS to estimate a direction (as he can use the stylus to see the 3d map of each LoS), instead of going to the whole-body view.
Task 3 – Looking for the black ribosome
He looks for black objects in the map, passing the stylus through it. As he doesn't know how a ribosome should look like, he doesn't pay attention to the geometry, only to the color and the text description.
Task 4 – Pointing the abnormalities
As all LoS are represented in the map, John infers that, except for the abnormalities that are not LoS, he can just look for them in the map. Also, because of the hierarchy path that is highlighted, John can also determine how to get there.
Task 5 – Listing visited and to-be-visited LoS
John can figure what LoS he has already visited by looking to the map. As he has all the LoS represented in the map, he can estimate what LoS he still needs to visit by looking for LoS that are labeled as abnormal.
Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor
As John passes the stylus over the DNA LoS that is below the red cell in the hierarchy, the description shows "altered DNA". He then figures that he should look for a DNA with the description "normal DNA", or something like that. He can manipulate the scale hierarchy map as he wants, so he is able to compare the 3d representation of the normal DNA to the abnormal one.

Spatial Orientation-based Technique

Background…

Task 1 – Finding the red cell

Now, John has a 3d map attached on his hand. He is in the whole body view LoS, and he can see the same thing in this 3d map. There are translucent boxes in each of the five organs represented there, so John infers that the LoS are marked this way. When he passes the wand over the LoS, he sees a textbox with the same description as in the scale hierarchy map tool. The pointed LoS also becomes translucent and bigger, allowing John to see what is inside of it. As he selects the right lung in the WIM, he notices that the map is zoomed to a new LoS, and now he can see what LoS are inside the lung. Once he finds a LoS with the description "red cell", he selects it to travel.

Task 2 – Determining which organ is closer

John uses the WIM to zoom out to the whole-body view. As he is doing that, he notices that there is a green dot blinking inside his current LoS, and that the LoS has become translucent. He infers that the green dot represents his current position. When he gets to the whole-body view, he sees the whole hierarchy path translucent, and the green dot showing him his real position. He figures that he only need to know if the green dot is closer to liver or to the heart.

Task 3 – Looking for the black ribosome

As John selects the liver in the WIM, he notices that the map is zoomed to a new LoS, and now he can see what LoS are inside the liver. Once he finds a LoS with the description "black ribosome", he selects it to travel.

Task 4 – Pointing the abnormalities

John can see all the LoS and the normal objects in the WIM. Using the zoom, John can determine where and how to get to each of the abnormalities.

Task 5 – Listing visited and to-be-visited LoS

John figures that he has to use zoom into each of the LoS to determine what LoS he has already visited. As he can explore the LoS without entering them, he uses the WIM and the lock feature to search for them.

Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor

John looks for LoS that has "DNA" in its description inside the red cell. By manipulating the SSWIM, he can compare the 3d representation of a normal DNA to the abnormal one that is in the normal view.

2D Top-View Map with Focus+Context Techniques

(very similar to the spatial orientation-based technique)

Background…

Task 1 – Finding the red cell

Now John has a 2d map attached to his tablet. He is in the whole body view LoS, and he can see a top view on this map. There are yellow spheres (think of something better than this to highlight LoS here) in each of the five organs represented there, so John infers that the LoS are marked this way. When he passes the stylus over the LoS, he sees a textbox with the same description as in the two previous tools. Increasing the level of zoom by selecting a zoom center, he is able to see the LoS that are inside the right lung and the other organs in the context area of the map. Once he finds a LoS with the description “red cell”, he selects it to travel. He notices that there is a green dot blinking inside his current LoS. He infers that the green dot represents his current position.

Task 2 – Determining which organ is closer

John uses the context area to determine which organ is closer.

Task 3 – Looking for the black ribosome

As John selects the liver area in the map, he notices that the focus area in the map changes to the liver, and now he can see what LoS are inside the liver. Once he finds a LoS with the description “black ribosome”, he selects it to travel.

Task 4 – Pointing the abnormalities

John can see all the LoS and the normal objects in the scene. Using the zoom/focus/context, John can determine where and how to get to each of the abnormalities.

Task 5 – Listing visited and to-be-visited LoS

John figures that he has to use zoom into each of the LoS to determine what LoS he already visited. As he can explore the LoS without entering them, just by adjusting the zoom level and the focus area, he looks for abnormalities in each level.

Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor

The level of zoom is presented as text to John, and he looks for the DNA level focusing in the red cell area. He can only compare the 2d representation.

Interaction Scenario

Scale Hierarchy-based Technique

Background…

Task 1 – Finding the red cell

John uses the stylus to look for the red cell. As he passes the stylus through the LoS, the system magnifies the LoS that he is pointing and turns it into its 3d representation and also shows a text description of it. John can lock the zoom by pressing a button, and the system will ignore the stylus until he unlocks it. When the zoom is locked, the system shows the hierarchy path from John’s position to the LoS in which John has locked the zoom. By releasing the stylus with the zoom unlocked, it goes back to zoom the current LoS. As soon as he finds the red cell, John presses the travel button, and the system translates him to the center of the desired scale (as the target-based travel technique).

Task 2 – Determining which organ is closer

John selects the whole-body view in the hierarchy tree using the lock button, and the system shows the 3d representation of it with the YAH marker and the hierarchy path. Then he selects the liver with the travel button, and the system moves him to the center of the liver, and his YAH is updated in the map. Finally, he selects the heart with the travel button, the system translates him to the heart and his YAH is updated so he can try to compare the distances.

Task 3 – Looking for the black ribosome

John uses the stylus to search for the black objects. As soon as he finds the black object that has "black ribosome" in the description, he selects it with the travel button and the system automatically translates him to the center of that object.

Task 4 – Pointing the abnormalities

John uses the stylus to search for abnormalities. Using the lock button on the LoS that contain the abnormalities, John can determine how to get there.

Task 5 – Listing visited and to-be-visited LoS

John uses the stylus to search for abnormalities he doesn't know.

Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor

John passes the stylus over the DNA LoS that is below the red cell in the hierarchy and the description shows "altered DNA", and he selects it with the travel button. He looks for a DNA with the description "normal DNA", and uses the lock button to be able to manipulate the 3d map and compare it to the abnormal DNA in front of him.

Spatial Orientation-based Technique

Background…

Task 1 – Finding the red cell

John uses the wand to point to the right lung in the WIM, and selects it with the WIM travel button. The system automatically changes the WIM to the right lung. John points to each of the LoS he sees and uses the lock button to make the pointed LoS translucent and bigger, so he can see what is inside (still in the WIM). As he doesn't find the red cell this way, he uses the WIM travel button in each LoS inside the right lung and repeats the process described above, until he find the red cell. Once he does, John uses the REAL travel button to travel to it, and the system moves him to the center of the selected scale.

Task 2 – Determining which organ is closer

John presses the zoom out button to change the LoS in the WIM, until he gets in the whole-body view. He then manipulates the WIM to see if he is closer to the heart or to the liver.

Task 3 – Looking for the black ribosome

John uses the wand to select the liver in the WIM with the WIM travel button, and the system changes the WIM to represent the liver. John points to each of the LoS he sees and uses the lock button to make the pointed LoS translucent and bigger, so he can see what is inside (still in the WIM). As he doesn't find the black ribosome this way, he uses the WIM travel button in each LoS inside the right lung and repeats the process described above, until he find the black ribosome. Once he does, John uses the REAL travel button to travel to it, and the system moves him to the center of the selected scale.

Task 4 – Pointing the abnormalities

John uses the zoom out button to get to the whole-body LoS in the WIM. John points to each of the LoS he sees and uses the lock button to make the pointed LoS translucent and bigger, so he can see what is inside (still in the WIM). He uses the WIM travel button in each LoS and explores all existing LoS. John uses the zoom out button until he gets to the whole-body view and he tries to point that direction.

Task 5 – Listing visited and to-be-visited LoS

John uses the zoom out button to get to the whole-body LoS in the WIM. John points to each of the LoS he sees and uses the lock button to make the pointed LoS translucent and bigger, so he can see what is inside (still in the WIM). He uses the WIM travel button in each LoS and explores all existing LoS.

Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor

John uses the WIM travel button to travel to the red cell in the WIM. There, he uses the lock button to see what is inside each LoS, and finds the DNA. He selects the DNA with the travel button and the WIM becomes a representation of it. John uses the zoom out until he finds another cell. He uses the WIM travel until he finds the DNA.

2D Top-View Map with Focus+Context Techniques

Background…

Task 1 – Finding the red cell

John passes the stylus over the yellow spheres in the map, and the text description appears. He uses the zoom focus button to zoom the right lung, and the map is distorted to zoom the lung without losing the whole context. John uses the zoom in with the stylus in the right lung, and the system shows the next level of zoom information in the map. He keeps looking with different levels of zoom, and when he finds it, he presses the travel to LoS button pointing to it in the map.

Task 2 – Determining which organ is closer

John can pan using the pan button, and see the second level of zoom in the liver or the heart. He can also press the zoom out button and see how close he is of each one.

Task 3 – Looking for the black ribosome

John passes the stylus over the yellow spheres in the map, and the text description appears. He uses the zoom focus button to zoom the liver, and the map is distorted to zoom the liver without losing the whole context. John uses the zoom in with the stylus in the liver, and the system shows the next level of zoom information in the map. He keeps looking with different levels of zoom, and when he finds it, he presses the travel to LoS button pointing to it in the map.

Task 4 – Pointing the abnormalities

John passes the stylus over the yellow spheres in the map, and the text description appears. He looks for every abnormality using the pan button and the zoom focus button in the map, in each level of zoom.

Task 5 – Listing visited and to-be-visited LoS

John passes the stylus over the yellow spheres in the map, and the text description appears. He looks for all the LoS and tries to remember which he has already visited and which he hasn't.

Task 6 – Finding the way to the red cell and looking how the DNA is altered by the tumor

John uses the zoom in until he finds the red cell. Inside of it, he uses the zoom focus button to find the DNA, and uses the travel button to travel to it (the zoom is active while the button is pressed, and it's position is relative to the stylus position). He then uses the zooms out button until he sees the red cell in the map, and uses the pan button to find another cell. Then, John zooms in to the DNA, and compare to the 2d representation.

Appendix B – User Study Documents

B.1 Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
In Research Projects Involving Human Subjects

Title of Project: **Evaluation of navigation techniques for multiscale virtual environments**

Investigators: Felipe Bacim de Araujo e Silva, Doug A. Bowman

I. PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study for the evaluation of two design approaches for navigating and understanding multiscale virtual environments. This research study how our different approaches help users to understand the relationship between different levels of scale. By collecting the quantitative data and qualitative user preference, our research will provide insights on how navigation techniques should be designed to achieve better user experience in multiscale virtual environments.

II. PROCEDURES

You will be asked to perform a set of navigation tasks using a tracking system. These tasks consist of searching for and navigating to several levels of scale with one of the proposed navigation techniques. Your role in these tests is that of evaluator of the software. We are not evaluating you or your performance in any way; you are helping us to evaluate our various menu selection interfaces. All information that you help us attain will remain anonymous. The time you take to do each task and other aspects of your interaction with the system will be measured and recorded. You will be asked questions after each session of usage of our system, in order to clarify our understanding of your evaluation.

You will also be asked to fill out a questionnaire relating to your background with such systems before any of the sessions.

The experiment will last for about one hour. The tasks are not tiring, but you are welcome to take rest breaks as needed. One scheduled rest break will be given to you between each session of the experiment. You may also terminate your participation at any time, for any reason.

You will be given full instructions before every task. If anything is unclear, be sure to ask us questions.

III. RISKS

The proposed sessions are straightforward tests of performance. Participation involves the use of a head mounted display, a tablet surface and a joystick. The physical components of these tasks are not stressful, and include changing your head orientation, using the joystick as your hand and holding the tablet. All light and sound intensities are well within normal ranges. The only foreseeable physical risks are slight eye and arm strain. There are minimal mental risks.

If you experience any eye or arm strain during a session, then between tasks please tell the experimenter so you can take a rest break. The experimenter will explain when you can take such rest breaks. If you have trouble with any task, please tell us.

IV. BENEFITS

Your participation in this project will provide information that may be used to improve the design of user interfaces for navigating in multiscale virtual environments. No guarantee of benefits has been made to encourage you to participate.

You are requested to refrain from discussing the evaluation with other people who might be in the candidate pool from which other participants might be drawn.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

VI. COMPENSATION

There is no monetary compensation for your participation.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason.

VIII. APPROVAL OF RESEARCH

This research has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University, and by the Department of Computer Science.

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project

____ ______________
Signature Date

____
Name (please print)

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Felipe Bacim de Araujo e Silva — Email: fbacim@gmail.com
Investigator

Doug A. Bowman — Email: bowman@vt.edu
Faculty Advisor — Phone: (540) 231-2058
Dept. of Computer Science
2202 Kraft Drive
Blacksburg, VA 24060

David M. Moore — Email: moored@vt.edu
Chair, Virginia Tech Institutional Review
Board for the Protection of Human Subjects
Office of Research Compliance
1880 Pratt Drive, Suite 2006 (0497)
Blacksburg, VA 24061

B.2 Background Survey

Background Survey

Please help us to categorize our user population by answering the following questions.

1. What is your gender?

    () Male   () Female

2. How old are you?

3. Are you wearing glasses or contact lenses during the experiment?

    () Glasses   () Contact Lenses   () No

4. Are you left or right handed?

    () Left   () Right

5. What is your occupation? (If you're a student, indicate graduate or undergraduate)

6. If you indicated you're a student in question 5, what is your major?

7. You are familiar with computers.

    () Strongly Disagree   () Disagree   () Neutral   () Agree   () Strongly Agree

8. How often do you use computers?

9. Please briefly describe your experience with virtual reality, if any.

10. Please briefly describe your experience with multiscale interfaces (e.g. Google Maps/Earth), if any.

B.3 Procedure

Multiscale Navigation Techniques:
Comparison of HiSMap, MSWIM and Target+Steering

Procedural Overview

1. Pre-screening:
    a) Confirm right-handedness
2. Consent Form (make sure they consent to have the interview recorded)
3. Background Survey
4. Tutorial
    a) MSWIM
    b) HiSMap
    c) MSWIM+HiSMap
    d) Target+Steering
5. Trials
6. Exit Interview

(MSWIM)

Start application in training mode.

I'd just like to remind you that we'll be recording the audio.

Now we're going to begin the first part of the experiment. For this part, we are going to have you complete some simple navigation tasks in a practice environment for you to familiarize with the techniques you will be using.

In our work, we're focusing on a specific type of VEs: Multiscale Virtual Environments (MSVEs). MSVEs contain several hierarchical levels of scale in the same environment. In other words, smaller scales are nested within larger scales. For example, cities are nested in a state, which is nested in a country, and so on. Consequentially, in a MSVE, you can be big enough to see all the big cities in a state, or "small" as a human to walk around a city.

OK, so first, I need you to stand here.

Now, I'm going to give you the devices you will be using.

This is the Head Mounted Display, and you will use it as a window to the virtual world. It will change your point of view in the virtual environment as you change your head orientation and position. Do you see this knobs here? You will use them to adjust the Head Mounted Display to your head size.

This is the tablet, which you will use to control the virtual tablet. You should hold it with your left hand. Notice the band behind of it, which you will put your hand.

This is the wand, which you will use to interact with/use the techniques. You should hold it with your right hand.

Notice the four buttons and the joystick on top of it. I'll be referring to them as the lower left, upper left and right buttons, OK? I'll explain what each of these buttons do when you're using the application.

Put everything on...

Go ahead and see how your point of view moves as you move you head. Also, move your hand and the tablet around and see how their virtual correspondents move.

Notice the little body on the upper right portion of the screen, and how it changes its orientation according to where you're looking. This will help you keep track of the direction of stuff you may be looking for. For example, this will give you the direction of the head when you're inside a level of scale.

Please let me know if you have any questions.

In this practice environment, you will be traveling through that spheres you see inside the body, and it is similar to the environment we're gonna be using in the actual experiment. The context of the experiment is traveling through different levels of scale inside the body, so this environment is a simplified version of how that is gonna look like. In the actual experiment, instead of spheres, you're gonna be traveling around organs.

Now we're going to go over how the MSWIM technique works.

As you can see, there is a miniature of the world over the tablet you're holding. This miniature of the world is called World-In-Miniature, and I'll be referring to it as WIM.

Now, try to move your right hand (the one holding the wand) inside the box that is over the tablet. See how the background color of the tablet changes? This is how you know that you are interacting with the miniature or with the actual environment.

Now, did you notice that the body in the miniature is translucent, and the organs are not? This means that the scale that is selected for interaction is the body, and that you will be able to see everything that is inside of it.

Try to touch one of the spheres with your virtual hand. Notice that a red box highlighted the scale that you just touched, and a text appears attached to it. This text describes what is the scale you just touched.

Also notice that, as you touch a sphere, not only it's miniature becomes highlighted, but the sphere becomes highlighted as well.

Go ahead and try to touch all the objects in the miniature and see what are they.

Please let me know if you have any questions.

Now we're going to go over how to navigate using this technique. To do this, you're going to be using the lower left button.

Try to touch a level of scale in the miniature and press the lower left button when you're doing it.

Notice how the level of scale selected for interaction changed to the one you were touching, and how it became translucent so you could see what is inside of it.

Notice that you can still touch and select the other organs, even though they are bigger.

If you decide that the level of scale that you just selected is not the one that you wanted, make sure your virtual hand is not touching anything, and press the lower left button (the same you used before).

Go ahead and play around with it a bit.

Please let me know if you have any questions.

Now we're going to go over a method for changing what you're seeing in the WIM. With the wand inside the WIM box and pointing forward, press the joystick up.

See how it looks like everything in the WIM starts to scroll on the opposite direction that you're pointing? Try to change your hand orientation and see how it goes.

If you want to reset the position, just make sure your virtual hand is not touching anything and press the lower left button.

Please let me know if you have any questions.

Now, select the level of scale that you want to visit; let's say, the grey scale inside the scale labeled "Training 1".

Okay, now, press the upper left button. Notice that, when you do that, the MSWIM disappears and you start traveling to the selected scale.

When you're traveling, the path to get to the selected destination is going to appear on the left side of the screen. In this case, it showed that you left the "full body" scale, went through the Training 1 and then got to the grey scale.

Did you notice the red arrow blinking? That shows you in which direction you're going; from the body to the Training 1, and once you got to the Training 1, from the Training 1 to the grey scale.

Also notice that the current level of scale will always appear in the center of the screen; hence why you saw the path "scrolling up".

Now, press lower left button to go back to the Training 1 scale in the WIM. See how grey scale became highlighted even though you're not touching it?

Also, notice that three lines crossing each other inside of it; that is your current position, and it is updated as you move around.

Play around with these things a bit and take your time to learn how to use this method.

Please let me know if you have any questions.

Another way to travel in the world is to use the steering technique. To do that, make sure that your hand is not inside the WIM. Now, with the wand pointing forward, press the joystick up.

As you can see, you're now traveling in the world.

Try to change the orientation of your hand when you're pressing the joystick; you'll see that you will travel towards the direction that you're point with your hand.

Now, go back to where we started and try to fly towards any of the scales. If you stop pressing the joystick after entering an organ, you will be automatically scaled down to it.

You can use this method to get out of it, as well. Try to get out of the scale you've entered.

Go ahead and play around with this method, and take your time to learn how to use it.

Please let me know if you have any questions.

Notice that, when the selected level of scale is not the body, a little body appears attached on the lower left portion of the WIM.

That body gives you reference to where you are in the WIM relative to it.

Also, if the selected scale in the WIM is not the same as your current scale in the world, two arrows will appear.

The one attached to the lower right part of the WIM, points to your current position in the real world relative to the selected scale in the WIM. You can use that to scroll to your current position.

The other arrow, the one attached to your hand, points to the position in the world of the selected scale.

Go ahead and play with all those orientation tips, and take your time to learn how to use this method.

Feel free to use the much time you want, and ask me if you have any questions. As soon as you feel ready for doing the trials with this technique, let me know.

Let’s take a 5 minutes break.

Multiscale Navigation Techniques:
Comparison of HiSMap, MSWIM and Target+Steering

Procedural Overview

1. Pre-screening:
    a) Confirm right-handedness
2. Consent Form (make sure they consent to have the interview recorded)
3. Background Survey
4. Tutorial
    a) MSWIM
    b) HiSMap
    c) MSWIM+HiSMap
    d) Target+Steering
5. Trials
6. Exit Interview

(HiSMap)

Start application in training mode.

I'd just like to remind you that we'll be recording the audio.

Now we're going to begin the first part of the experiment. For this part, we are going to have you complete some simple navigation tasks in a practice environment for you to familiarize with the techniques you will be using.

In our work, we're focusing on a specific type of VEs: Multiscale Virtual Environments (MSVEs). MSVEs contain several hierarchical levels of scale in the same environment. In other words, smaller scales are nested within larger scales. For example, cities are nested in a state, which is nested in a country, and so on. Consequentially, in a MSVE, you can be big enough to see all the big cities in a state, or "small" as a human to walk around a city.

OK, so first, I need you to stand here.

Now, I'm going to give you the devices you will be using.

This is the Head Mounted Display, and you will use it as a window to the virtual world. It will change your point of view in the virtual environment as you change your head orientation and position. Do you see this knobs here? You will use them to adjust the Head Mounted Display to your head size.

This is the tablet, which you will use to control the virtual tablet. You should hold it with your left hand. Notice the band behind of it, which you will put your hand.

This is the wand, which you will use to interact with/use the techniques. You should hold it with your right hand.

Notice the four buttons and the joystick on top of it. I'll be referring to them as the lower left, upper left and right buttons, OK? I'll explain what each of these buttons do when you're using the application.

Put everything on...

Go ahead and see how your point of view moves as you move you head. Also, move your hand and the tablet around and see how their virtual correspondents move.

Notice the little body on the upper right portion of the screen, and how it changes its orientation according to where you're looking. This will help you keep track of the direction of stuff you may be looking for. For example, this will give you the direction of the head when you're inside a level of scale.

Please let me know if you have any questions.

In this practice environment, you will be traveling through that spheres you see inside the body, and it is similar to the environment we're gonna be using in the actual experiment. The context of the experiment is traveling through different levels of scale inside the body, so this environment is a simplified version of how that is gonna look like. In the actual experiment, instead of spheres, you're gonna be traveling around organs.

Now we're going to go over and see how the HiSMap technique works.

As you can see, there is a bunch of icons connected by blue lines on the tablet you're holding. Each icon represents a specific level of scale, and the lines connect nested levels of scale. The row in which these icons are represents how many scales nests the level of scale illustrated by the icon.

For example, the body is not nested, so it goes in row one, but the spheres are nested by the body, so they go to the second row and a line connects all spheres to the body, so you know that they're nested in the body and not anything else.

As you can see, the model at the top of the hierarchy is the body, and it is represented in 3d and not a icon because it is your current position in the hierarchy.

Now, try to move your right hand (the one holding the wand) and touch those icons right below the body. Notice that the icon you've touched grew and became a 3d model.

Also, notice that a green box highlighted the scale that you just touched, and a text appears attached to it. This text describes what is the scale you just touch.

Also notice that, as you touch an icon, not only the icon becomes highlighted, but the sphere that the icon represents becomes highlighted as well.

Go ahead and try to touch all the objects in the miniature and see what are they.

Please let me know if you have any questions.

Now, find the scale named "Training 3" and press the lower left button on the wand.

This indicates that you've selected the scale that you were touching, and that it will remain selected even when you're not touching it anymore.

Notice that the body turned into an icon but did not shrink and the line that connected the body to the liver turned red. Those signs mean that the body is in the path to be followed to get to the selected scale.

Also notice that there is a yellow arrow blinking above the body icon. This arrow indicates that the body is your current position in the world.

Now, move your right hand over other scales in the hierarchy and notice that a red box just highlighted the icon, and the text description was attached to it, but it not grew or turned into a model. This means that, although the selected scale remains the same as before, you still can see what are the other scales in the hierarchy.

Please let me know if you have any questions.

Now, select the level of scale that you want to visit; let's say, the grey scale inside the scale named "Training 1".

Okay, now, press the upper left button. Notice that, when you do that, the MSWIM disappears and you start traveling to the selected scale.

When you're traveling, the path to get to the selected destination is going to appear on the left side of the screen. In this case, it showed that you left the "full body" scale, went through the Training 1 and then got to the grey scale.

Did you notice the red arrow blinking? That shows you in which direction you're going; from the body to the Training 1, and once you got to the Training 1, from the Training 1 to the grey scale.

Also notice that the current level of scale will always appear in the center of the screen; hence why you saw the path "scrolling up".

Now, press lower left button to go back to the Training 1 scale in the WIM. See how grey scale became highlighted even though you're not touching it.

Also, notice that three lines crossing each other inside of it; that is your current position, and it is updated as you move around.

Please let me know if you have any questions.

Another way to travel in the world is to use the steering technique. To do that, make sure that your hand is not inside the WIM. Now, with the wand pointing forward, press the joystick up.

As you can see, you're now traveling in the world.

Try to change the orientation of your hand when you're pressing the joystick; you'll see that you will travel towards the direction that you're point with your hand.

Now, go back to where we started and try to fly towards any of the scales. If you stop pressing the joystick after entering an organ, you will be automatically scaled down to it.

You can use this method to get out of it, as well. Try to get out of the scale you've entered.

Go ahead and play around with this method, and take your time to learn how to use it.

Please let me know if you have any questions.

Multiscale Navigation Techniques:
Comparison of HiSMap, MSWIM and Target+Steering

Procedural Overview

1. Pre-screening:
    a) Confirm right-handedness
2. Consent Form (make sure they consent to have the interview recorded)
3. Background Survey
4. Tutorial
    a) MSWIM
    b) HiSMap
    c) MSWIM+HiSMap
    d) Target+Steering
5. Trials
6. Exit Interview

(MSWIM)

Start application in training mode.

I'd just like to remind you that we'll be recording the audio.

Now we're going to begin the practice session. For this part, we are going to go over all you have seen in the video in a practice environment for you to familiarize with the techniques you will be using.

OK, so first, I need you to stand here.

Now, I'm going to give you the devices you will be using.

The Head Mounted Display. Do you see this knobs here? You will use them to adjust the Head Mounted Display to your head size.

The tablet. You should hold it with your left hand. Notice the band behind of it, which you will put your hand.

The wand. You should hold it with your right hand.

Remember the four buttons and the joystick on top of it? The lower left, upper left and right buttons?

Put everything on...

Go ahead and see how your point of view moves as you move you head. Also, move your hand and the tablet around and see how their virtual correspondents move.

Take a look at the little body on the upper right portion of the screen, and how it changes its orientation according to where you're looking.

Please let me know if you have any questions.

Notice the world in miniature over the tablet you're holding.

Now, try to move your right hand (the one holding the wand) in and out of the box that is over the tablet and see the background color changing.

Take a look at the body in the miniature, and see how it is translucent, and the organs are not. This means that the scale that is selected for interaction is the body, and that you will be able to see everything that is inside of it.

Try to touch the spheres with your virtual hand and notice the red box highlighting them, and their text description.

Also notice that, as you touch a sphere, not only it's miniature becomes highlighted, but the sphere becomes highlighted as well.

Now, try to touch a level of scale in the miniature and press the lower left button when you're touching to select it. Notice how the level of scale selected for interaction changed.

Well, remember that if you want to go back to the body, just make sure your virtual hand is not touching anything an press the lower left button.

Please let me know if you have any questions.

Now, try to use the joystick with the wand inside the WIM box to scroll what you're seeing.

Remember, if you want to reset the position, just make sure your virtual hand is not touching anything and press the lower left button.

Please let me know if you have any questions.

Now, select the grey scale inside the scale labeled “Training 1”, and press the upper left button to travel there. Notice the path to get to the green scale on the left side of the screen.

Now, press the lower left button to go back to the Training 1 scale in the WIM and see how the green scale became highlighted. Also, remember that the three lines crossing each other inside of it represent your current position.

Please let me know if you have any questions.

Notice the little body attached on the lower right portion of the WIM.

Also notice the two arrows that appear when the selected scale in the WIM is not the same as your scale in the world.

Remember that the one attached to the lower right part of the WIM, points to your current scale in the real world relative to the selected scale in the WIM.

The other arrow, the one attached to your hand, points to the position in the world of the selected scale.

Please let me know if you have any questions.

Remember you can use the steering technique to travel as well. Just make sure that your hand is not inside the WIM and, with the wand pointing forward, press the joystick up.

Try to change the orientation of your hand when you’re pressing the joystick; you’ll see that you will travel towards the direction that you’re point with your hand.

Try to enter or leave a level of scale using this technique.

Please let me know if you have any questions.
(HiSMap)

Now, press any of the right buttons to switch to the hierarchical map.

Notice the icons over the tablet and how they relate to each other with the lines.

Try to touch the icons to see how they become highlighted and their descriptions appear attached to them. Notice the path that is formed between your current scale and the selected scale.

Press the lower left button when touching an icon to select it.

Touch the other icons now to see how they are highlighted.

Press the lower left button when not touching any object to deselect and see how your current scale becomes highlighted.

Now, select a scale and press the upper left button to travel.

Remember you can use the steering technique with the hierarchy. Try to enter or leave a level of scale and see how the scale that is highlighted in the hierarchy changed to the one you entered.

Now, select a level of scale in hierarchy and press any of the right buttons. Notice that the scale that you selected in the hierarchy is now the scale selected for interaction in the WIM.

Feel free to practice now, and ask me if you have any questions. As soon as you feel ready for doing the trials, let me know.

Let’s take a 5 minutes break.

**Multiscale Navigation Techniques:
Comparison of HiSMap, MSWIM and Target+Steering**

Procedural Overview

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    c) MSWIM+HiSMap
    d) Target+Steering
5. Trials
6. Exit Interview

(Target+Steering)

Start application in training mode.

I'd just like to remind you that we'll be recording the audio.

Now we're going to begin the first part of the experiment. For this part, we are going to have you complete some simple navigation tasks in a practice environment for you to familiarize with the techniques you will be using.

In our work, we're focusing on a specific type of VEs: Multiscale Virtual Environments (MSVEs). MSVEs contain several hierarchical levels of scale in the same environment. In other words, smaller scales are nested within larger scales. For example, cities are nested in a state, which is nested in a country, and so on. Consequentially, in a MSVE, you can be big enough to see all the big cities in a state, or "small" as a human to walk around a city.

OK, so first, I need you to stand here.

Now, I'm going to give you the devices you will be using.

This is the Head Mounted Display, and you will use it as a window to the virtual world. It will change your point of view in the virtual environment as you change your head orientation and position. Do you see this knobs here? You will use them to adjust the Head Mounted Display to your head size.

This is the wand, which you will use to navigate. You should hold it with your right hand.

Notice the four buttons and the joystick on top of it. I'll be referring to them as the lower left, upper left and right buttons, OK? I'll explain what each of these buttons do when you're using the application.

Put everything on...

Go ahead and see how your point of view moves as you move you head. Also, move your hand and the tablet around and see how their virtual correspondents move.

Notice the little body on the upper right portion of the screen, and how it changes its orientation according to where you're looking. This will help you keep track of the direction of stuff you may be looking for. For example, this will give you the direction of the head when you're inside a level of scale.

Please let me know if you have any questions.

In this practice environment, you will be traveling through that spheres you see inside the body, and it is similar to the environment we're gonna be using in the actual experiment. The context of the experiment is traveling through different levels of scale inside the body, so this environment is a simplified version of how that is gonna look like. In the actual experiment, instead of spheres, you're gonna be traveling around organs.

Now we're going to go over and see how the Target+steering technique works. As you can see, there is a magnifying glass attached to your right hand. You will be using it to select and navigate to different levels of scale.

Look down now, and you will see an open body, with a bunch of spheres inside. Try to point the magnifying glass to one of these sphere, as if you were looking through it.

See how the sphere that is nearer to the center of the magnifying glass became highlighted by a yellow box? This means that this is the selected scale for navigation. Notice that, as you point to a level of scale, it's name appears attached to the magnifying glass.

Now, did you notice that some of the other spheres were also highlighted, but by a black wireframe box? This means that they are visible through the magnifying glass, but they're not in the center.

Please let me know if you have any questions.

Now, when pointing to one of the spheres, try to press the lower left button. Notice that, when you do that, you start traveling to the level of scale that you were pointing.

Did you notice that, after entering a scale, a translucent sphere with a blinking green sphere appeared in the upper left portion of the screen? The translucent sphere is a 3d map of your current scale, and the blinking green sphere is your current position in it.

Try to move around and see how the green sphere changes its position, and how the map changes its orientation according to your head orientation, just like the body in the upper right corner.

Now, if you decide that the level of scale you've just entered is not the one you wanted, press the upper left button to go back to the previous level of scale; in this case, the body.

Go ahead and play around with this method, and take your time to learn how to use it. Please let me know if you have any questions.

Another way to travel in the world is to use the steering technique. To do that, with the wand pointing forward, press the joystick up.

As you can see, you're now traveling in the world.

Try to change the orientation of your hand when you're pressing the joystick; you'll see that you will travel towards the direction that you're point with your hand.

Now, go back to where we started and try to fly towards any of the scales. If you stop pressing the joystick after entering a sphere, you will be automatically scaled down to it.

You can use this method to get out of it, as well. Try to get out of the scale you've entered.

Go ahead and play around with this method, and take your time to learn how to use it.

Let's take a 5 minutes break.

Multiscale Navigation Techniques:
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Procedural Overview

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6. Exit Interview

Trials:

Start application in experiment mode.

Ok, so in the practice session, you traveled through spheres inside the human body. Now, for the experiment, your tasks will involve navigation through organs inside the body, tumors inside the organs, cells inside the tumors, and so on, until the DNA.

Remember, the purpose of this study is to collect empirical data in order to compare the pros and cons of different designs, we are NOT evaluating you in anyway.

Please, remember to only start to do a task after I say so, and let me know when you consider it done, as I'll be measuring time. I'll black out the screen while I'm explaining the task to you, and I'll only turn it on again when you consider yourself ready for doing the task. I'll tell you "you may begin" so you know when to start doing the task.

PRESS THE 'b' *KEY.*

Your first task is to find the level of scale labeled abnormal cell and travel to it in the actual environment. So, again, you'll have to find the abnormal cell and go there. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and remember to tell me when you're done. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* '\]' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '2' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

You task now is to tell me if you are closer to the heart or to the liver. So, again, your task is to tell me if you are closer to the heart or to the liver. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE '*[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '2' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Now, your task is to compare the abnormal cell to a normal cell and tell me what is the difference between them. Again, your task is to compare the abnormal cell to a normal cell and tell me what is the difference between them. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE '*[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '2' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Your next task is to use the steering technique to go to the red cell. Again, your task is to use the steering technique to navigate to the level of scale labeled red cell. You can use the techniques you've learned to figure out how to get there, but you can only travel using the steering technique. Do it as quick and efficient as you can, and remember to tell me when you're done. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '2' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Now your task is to tell me in which of the organs you were and through which levels of scale would you pass to get there again, without using the techniques. Again, your task is to tell me in which of the organs you were and through which levels of scale would you pass to get there again, without using the techniques. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

Do you need a break?

PRESS THE 'b' *KEY. PRESS THE* '1' *KEY.*

Now your task is to find the level of scale labeled abnormal ribosome and travel to it in the actual environment. Again, you have to find the abnormal ribosome and go there. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and remember to tell me when you're done. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '3' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

There are 3 ribosome inside each cell, and you are inside one of them. Your task is to tell me if it is the one closer to the head, the one closer to the left lung or the one closer to the right lung. Again, your task is to tell me if you are in the ribosome that is closer to the head, the one closer to the left lung or the one closer to the right lung. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE '*[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '3' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Compare the abnormal ribosome to a normal ribosome and tell me what is the difference between them. Again, you have to tell me what's the difference between an abnormal ribosome and a normal one. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE '*[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '3' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Your next task is to use the steering technique to go to the scale labeled black ribosome. Again, your task is to use the steering technique to go to the black ribosome. You can use the techniques you've learned to figure out how to get there, but you can only travel using the steering technique. Do it as quick and efficient as you can, and remember to tell me when you're done. Do you have any questions? Are you ready to begin the task?

PRESS THE ‘b’ *KEY.* You may begin. *PRESS THE ‘*[‘ *KEY.*

“I’m done”. *PRESS THE* ‘]’ *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE ‘3’ KEY. PRESS THE ‘b’ *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Now your task is to tell me in which of the organs you were and through which levels of scale would you pass to get there again, without using the techniques. Again, your task is to tell me in which of the organs you were and through which levels of scale would you pass to get there again, without using the techniques. You can use the technique you prefer, or you can alternate between the ones you’ve learned. Do it as quick and efficient as you can, and I’ll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE ‘b’ *KEY.* You may begin. *PRESS THE ‘*[‘ *KEY.*

“I’m done”. *PRESS THE* ‘]’ *KEY.*

Do you need a break?

PRESS THE ‘b’ *KEY. PRESS THE* ‘1’ *KEY.*

So, you task now is to find the level of scale labeled abnormal nucleus and travel to it in the actual environment. Again, you have to find the abnormal nucleus and go there. You can use the technique you prefer, or you can alternate between the ones you’ve learned. Do it as quick and efficient as you can, and remember to tell me when you’re done. Do you have any questions? Are you ready to begin the task?

PRESS THE ‘b’ *KEY.* You may begin. *PRESS THE ‘*[‘ *KEY.*

“I’m done”. *PRESS THE* ‘]’ *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE ‘4’ KEY. PRESS THE ‘b’ *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Your next task is to tell me if you are closer to the heart or to the stomach. Again, you have to tell me if you are closer to the heart or to the stomach You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer.. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '4' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Now your task is to compare the abnormal nucleus to a normal nucleus and tell me what is the difference between them. Again, you have to tell me what is the difference between an abnormal nucleus and a normal one. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '4' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Your next task is to use the steering technique to go to the green nucleus. Again, you have to use the steering technique to navigate to the green nucleus. You can use the techniques you've learned to figure out how to get there, but you can only travel using the steering technique. Do it as quick and efficient as you can, and remember to tell me when you're done. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '4' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Now your task is to tell me in which of the organs you were and through which levels of scale would you pass to get there again, without using the techniques. Again, your task is to tell me in which of the organs you were and through which levels of scale would you pass to get there again, without using the techniques. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

Do you need a break?

PRESS THE 'b' *KEY. PRESS THE* '1' *KEY.*

Now your task is to find the scale labeled abnormal chromosome and travel to it in the actual environment. Again, you have to find the abnormal ribosome and go there. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and remember to tell me when you're done. Do you have any questions? Are you ready to begin the task?

You may begin. *PRESS THE* '[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '5' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Now, your task is to tell me if you are closer to the right lung or to the stomach. Again, you have to tell me if you are closer to the right lung or to the stomach. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE ‘b’ *KEY.* You may begin. *PRESS THE ‘*[‘ *KEY.*

“I’m done”. *PRESS THE* ‘]’ *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE ‘5’ KEY. PRESS THE ‘b’ *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Compare the abnormal chromosome to a normal chromosome and tell me what is the difference between them. Again, you have to tell me what is the difference between the abnormal chromosome and a normal chromosome. You can use the technique you prefer, or you can alternate between the ones you’ve learned. Do it as quick and efficient as you can, and I’ll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE ‘b’ *KEY.* You may begin. *PRESS THE ‘*[‘ *KEY.*

“I’m done”. *PRESS THE* ‘]’ *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE ‘5’ KEY. PRESS THE ‘b’ *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Your next task is to use the steering technique to go to the scale labeled yellow chromosome. Again, you have to use the steering technique to go to the scale labeled yellow chromosome. You can use the techniques you’ve learned to figure out how to get there, but you can only travel using the steering technique. Do it as quick and efficient as you can, and remember to tell me when you’re done. Do you have any questions? Are you ready to begin the task?

PRESS THE ‘b’ *KEY.* You may begin. *PRESS THE ‘*[‘ *KEY.*

“I’m done”. *PRESS THE* ‘]’ *KEY.*

In a scale from 1 to 10, being 1 the hardest and 10 easiest, rate the ease of accomplishing this last task using the techniques. Please explain.

PRESS THE '5' KEY. PRESS THE 'b' *KEY. If using the target+steering techniques, check if there is a need to reset the position.*

Now your task is to tell me in which of the organs you were and through which levels of scale would you pass to get there again, without using the techniques. You can use the technique you prefer, or you can alternate between the ones you've learned. Do it as quick and efficient as you can, and I'll consider it done as soon as you tell me the answer. Do you have any questions? Are you ready to begin the task?

PRESS THE 'b' *KEY.* You may begin. *PRESS THE '*[' *KEY.*

"I'm done". *PRESS THE* ']' *KEY.*

You're done.

Multiscale Navigation Techniques:
Comparison of HiSMap, MSWIM and Target+Steering

Procedural Overview

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    d) Target+Steering
5. Trials
6. Exit Interview

Now please stand next to the computer for the interview.

Did you get lost any time? Why?

What did you prefer to use to navigate? Steering or ...? Why?

How well do you think you understand the spatial layout of the body after using this technique?

How much do you think the technique contributed for the understanding of the spatial layout?

How well do you think you understand the hierarchical structure of the levels of scale after using this technique?

Can you list what is the levels of scale order, or what is nested by what?

How much do you think the technique contributed for the understanding of the hierarchical structure?

Was there ever a time when you felt the technique was providing you with too much information?

Was there ever a time when you felt the technique was providing you with not enough information?

Was there anything about the technique that made you get confused, instead of helping you?

What was the best thing about this technique for completing the tasks?

What was the worst thing about this technique for accomplishing the tasks?

Appendix C – Paper Published at IEEE 3DUI 2009 Conference

Wayfinding Techniques for MultiScale Virtual Environments

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ABSTRACT

Wayfinding in multiscale virtual environments can be rather complex, as users can and sometimes have to change their scale to access the entire environment. Hence, this work focuses on the understanding and classification of information needed for travel, as well as on the design of navigation techniques that provide this information. To this end, we first identified two kinds of information necessary for traveling effectively in this kind of environment: hierarchical information, based on the hierarchical structure formed by the levels of scale; and spatial information, related to orientation, distance between objects in different levels of scale and spatial localization. Based on this, we designed and implemented one technique for each kind of information. The developed techniques were evaluated and compared to a baseline set of travel and wayfinding aid techniques for traveling through multiple scales. Results show that the developed techniques perform better and provide a better solution for both travel and wayfinding aid.

Index Terms: I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality

1 INTRODUCTION

Navigation in Virtual Environments (VEs) consists of actions that allow users to change their position and orientation, which are known as travel, and wayfinding, which is the planning and choice of routes to be followed within the environment and the cognitive process of building spatial knowledge [1].

Presenting large amounts of information at the same time can cause problems for the interfaces in general, because there is too much to see and navigation becomes difficult [6]. For more than a decade, researchers have been trying to solve this problem by developing techniques for structuring information on different levels of scale [18]. The levels of scale are determined by their semantic content, and they have specific settings for the amount and size of information users will be able to see and interact with.

MultiScale VEs (MSVEs) contain several hierarchical levels of scale in the same environment, in which smaller scales are nested within larger scales [10]. In MSVEs, the levels of scale can be either a place or an object. For example, cities are nested in a state, states are nested in a country, and so on. Being at the country level of scale, it would be possible to see all the states in a country and have a broader view of the VE, but being at the human level of scale, it would be possible to walk around a city and look at the details of the texture of a building.

Nevertheless, the understanding of such structures can be complicated. For example, in the world we know, objects range from $10^{-16}m$ (size of the smaller elementary particles) to $10^{26}m$ (size of the universe). These levels of scale are far from what a human being can interact with, which range from millimeters ($10^{-3}m$) to tens of meters ($10^{1}m$). This fact makes it difficult or even impossible to observe and understand these different levels of scale, and also to interact directly with many of the existing structures in the real world [18].

For this reason, users need a set of techniques that allow for the adjustment of their size and that also automatically adjust navigation parameters when they change their level of scale, such as users' height in the environment (if there is a floor), the speed at which they travel, what they can reach or see and, if using stereo, the distance between the users' eyes.

Although researchers have investigated methods for traveling between levels of scale [13] [10], there is a need for better wayfinding aids to allow users to make sense of these complicated environments. Thus, the main question that remains is how well the existing techniques can provide wayfinding aid. Depending on the number of levels of scale in the MSVE, it may be too hard for users to figure how to get from one level of scale to other levels. Research in this kind of environment is necessary to remedy this.

The main objectives of the research reported in this paper are to identify what information is necessary to navigate effectively in MSVEs and to design and implement navigation techniques for MSVEs that combine travel and wayfinding aids. This research will help us begin to understand the process by which humans can navigate multi-scale environments.

2 RELATED WORK

The study of MSVEs is important because it has a large number of applications, such as navigating the cosmos [13] or a whole-plane terrain [15], understanding of chemical experiments in a virtual laboratory [7], visualization of biological structures [17] and geospatial data [8] and study of anatomy [10]. All these applications can use multiple scales because they can be divided into several levels of scale, grouped and organized in a hierarchical structure.

A number of travel techniques have indirectly acknowledged that users understand VEs at different levels of scale by providing a handheld miniature version of the world [14] [9], which may in some cases be scaled up or down [16]. These tools provide wayfinding cues to the user, but assume that there are only two important levels of scale - overview and detail. We extend this idea to our MultiScale World-In-Miniature (MSWIM) technique by adding explicit support for hierarchies of scale.

The set of techniques for traveling through large-scale VEs, developed by Pierce [11], could be applied to MSVEs. Visible landmarks' are points of reference that become visible by having a scale factor applied to them from any point of the environment and serve as a reference to travel. The technique place representations' divides the VE into semantic units represented in a hierarchy and, instead of showing the distant visible landmarks, gives the user a representation of what its semantic unit contains. The combination of these two techniques allows users to travel large distances with a small number of commands, but do not provide cues about the hierarchy. We extend this idea in our Hierarchically-Structured Map (HiSMap) technique by providing representations of all levels of scale and the hierarchy formed by them.

Some tools for traveling through different levels of scale have been developed, such as the technique of pointing to the desired level of scale [13] and those based on target selection and steering.

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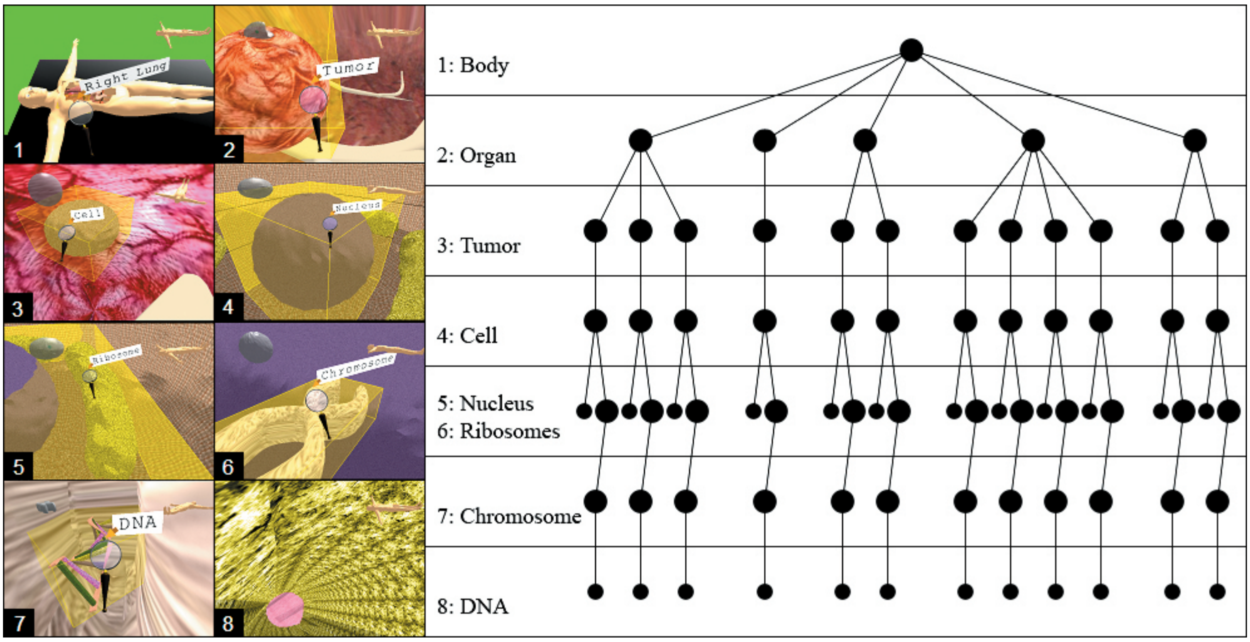

Figure 1: All the levels of scale and the hierarchical structure formed by them.

These techniques do not provide wayfinding cues. For this reason, Kopper uses two techniques commonly used in normal VEs: a three-dimensional map containing a You-Are-Here (YAH) marker and a compass represented as the human body. The map is a representation of users' current scale, while the compass indicates the orientation of users relative to the highest level of scale, which is the body. These techniques provide limited wayfinding cues and were not evaluated.

3 Wayfinding in MSVEs

As shown, there have been only a few travel techniques developed for MSVEs, and none of them concern aiding wayfinding tasks in such complex VEs. Although Kopper has implemented the wayfinding aids described in the related work section, wayfinding was not his focus and he did not carry out a study on its efficiency. Therefore, the focus of this work is on the development of new wayfinding aid techniques, specifically designed for MSVEs. To do this, we identified two types of information necessary to travel in MSVEs: spatial and hierarchical information.

Spatial information is all that concerns position and orientation of users, objects or specific places in a VE. It can be used to determine distances, landmarks position and directions. In the case of MSVEs, it concerns the levels of scale. Spatial information is the basis of most of the existing wayfinding aid techniques, such as the compass [2], signs [4] and maps [5]. With spatial information, it is possible to determine in which direction to go to get to a specific level of scale, where this level of scale is positioned, and what is the orientation of a level of scale in relation to others.

Hierarchical information is all information relative to the hierarchical structure formed by the levels of scale, such as in which levels of scale there is a certain tumor, or in which organ the user is, and so on. It helps users to know and understand the relationships between different levels of scale, independently of their position in space or scale.

The difference between these two kinds of information is that hierarchical information is abstract, i.e. it shows that a level of scale is nested in another level of scale, while the spatial information is concrete, i.e it indicates where this level of scale is located inside the other. For instance, if the user is inside the right lung, and decides to go to the left lung, hierarchical information would tell her that she needs to leave the right lung to be in the body scale, and then would need to enter the left lung. In this example, the spatial information would tell her where the left lung is located in the body and in which direction she would have to travel to get there from the right lung.

Table 1 describes the spatial and hierarchical information we have assumed as needed for traveling effectively in MSVEs and a summary of the extent of information provided by the designed techniques.

4 Research Testbed

The application used for this study is a modified version of that developed by Kopper [10], which simulates the study of anatomy. In this application, the levels of scale are the human organs and the objects that are inside them.

In order to diminish unnecessary cognitive load, the hierarchy and the levels of scale in the application have been designed to be part of the same context. We formed the following hierarchical structure: organs are nested in the body, tumors are nested in the organs, cells are nested in the tumors, ribosomes and nuclei are nested within the cells, chromosomes are nested in the nuclei and the DNA chains are nested in the chromosomes.

Similarly, we wanted to create a structure that is at the same time big and complex enough in terms of number of levels of scale, so we can understand how users gain and keep spatial and hierarchical knowledge, and at the same time simple, in terms of what users have to learn about it. To achieve this, we created a number of tumors inside the organs, and made all the tumors have one cell. All cells contained the complete hierarchical structure within them: the nucleus and ribosomes, the chromosome and the DNA. The resulting structure and the levels of scales can be seen in Figure 1.

The creation of this new environment was the starting point for the development of the new techniques. We also created a practice world, which is a simplified version of the environment used in the experiment; users travel through spheres inside a body.

Table 1: Table describing the identified wayfinding information and the amount of wayfinding information each technique provides.

Type	Provided information	Baseline Techniques	HiSMap	MSWIM
Spatial	Current position relative to the top level of scale	Moderate-quality information about position in current level of scale and orientation relative to the world; no information about other aspects	Moderate-quality about most spatial aspects	High-quality information about all spatial aspects
	Current position relative to the current level of scale			
	Current position relative to other level of scale			
	Orientation relative to the top level of scale			
	Target level of scale position relative to the top level of scale			
	Target level of scale position relative to the current level of scale			
	Target level of scale position relative to other level of scale			
	Target level of scale orientation			
Hierarchical	Current position	No information provided	High-quality information about all hierarchical aspects	Moderate- to high-quality about most hierarchical aspects
	Current position relative to lower level of scale			
	Current position relative to higher level of scale			
	Other level of scale at the same hierarchical level			
	Target level of scale position			
	Target level of scale position relative to lower levels of scale			
	Target level of scale position relative to higher levels of scale			
	Target level of scale position relative to others at the same level			

5 Designed Techniques

Having defined the necessary information needed for navigating in MSVEs, we designed the new navigation techniques using a design technique called scenario-based design [3]. Although these techniques were implemented in the context of the anatomy application, they were designed for use in any three-dimensional MSVE with a hierarchy of levels of scale.

Before describing specific features of each technique, it is important to highlight some of the features shared by them. With both techniques, users have a virtual hand attached to their right hand. The virtual hand is used to interact with and use the techniques. They also have the possibility of using the steering technique to maneuver within a level of scale, or even enter and leave levels of scale. The compass, described by Kopper, is always provided, independently of the technique used. The developed techniques also use two buttons for interaction: the **selection button**, which allows users to select and deselect levels of scale for interaction; and the **travel button**, which allow users to travel automatically to the selected level of scale.

The hardware requirements for all techniques include a head-tracked VR display and a 6-DOF handheld input device with at least two buttons and a joystick. The developed techniques also use a handheld tablet tracked in 6-DOF. The tablet worked as a physical prop to a virtual tablet, which displays the technique on top of it.

5.1 Baseline Techniques

We combined the techniques developed by Kopper, so that users have the ability to quickly change their level of scale with the target-based technique, and also to be able to maneuver and explore new levels of scale using the steering-based technique. In the target-based technique, the user have a magnifying glass metaphor to view and select a level of scale, and then travel automatically to it. With the steering-based technique, users have to fly towards the desired level of scale and enter it to be automatically scaled. We used the magnifying glass to view and select levels of scale with the target technique, and as a substitute of the virtual hand.

In addition, an important feature was added to the magnifying glass to help users build spatial knowledge: a text describing what the scale is that has been selected for interaction. Whenever the magnifying glass is being used to view the levels of scale that could be selected, the text description appears attached to it, as in Figure 1. Table 1 contains a list of wayfinding information provided by the combination of the techniques, and how well this information is provided.

5.2 MSWIM Technique

The MultiScale World-In-Miniature (MSWIM) technique is based on spatial information and was inspired by the Scaled Scrolling WIM [16], a modified version of the original WIM technique that allows users to zoom and pan what they are seeing in miniature. With the MSWIM, users can view the objects in the world, but cannot manipulate them. Also, there is no user representation in the miniature. Instead, users use the MSWIM to view and select levels of scale so that they can easily travel between different levels of scale, determine spatial position of specific objects, distance between objects, orientation, etc.

The MSWIM is located inside a box over the virtual tablet, and the selected scale for interaction always appears as a translucent object. Levels of scale that are at the same level of the hierarchy or are inside the selected one are opaque and selectable.

As the virtual hand touches the levels of scale inside the body, a red box highlights the scale they are touching and a text appears attached to it describing what the scale is. In addition, as users touch a level of scale, not only does its miniature become highlighted, but the object that represents the level of scale becomes highlighted as well.

To change the selected level of scale for interaction in the MSWIM, users have to press the selection button when touching a level of scale. Then, the selected level of scale increases in size and becomes translucent so that users can see and interact with levels of scale inside the one they have selected. The change of level of scale for interaction is animated to enable users to have a better understanding of the context in which the selected scale is. To go back to the previous level of scale, users just have to press the selection button when not touching anything with the virtual hand. It is also possible to pan and change the portion of the selected level of scale that will be seen in the box.

To travel using this technique, users select the level of scale to which they want to travel and press the travel button. Once the button is pressed, the MSWIM disappears and the user starts traveling to the selected scale. Figure 2 shows an example of how this happens when a cell is selected for travel.

When traveling, the path to get to the selected destination appears on the left side of the screen, and a blinking red arrow indicates the direction of travel: from the body to the right lung, and

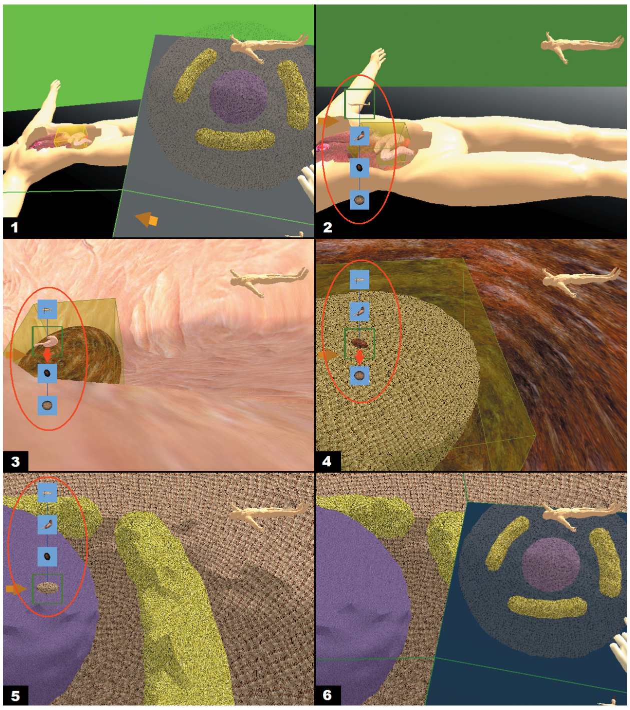

Figure 2: Animation of travel between two different levels of scale showing the user with the cell selected (1), starting to travel (2), passing through the body (3) and the tumor (4), and finally getting into the cell (5 and 6) and the hierarchy path being covered (highlighted in 2, 3, 4 and 5 by a red circle).

from the right lung to the white tumor. In addition to this, the current level of scale always appears in the center of the screen; hence the path is scrolling up in Figure 2.

If the user selects a higher level of scale in the WIM, the scale in which the user is becomes highlighted. Also, three lines crossing each other inside it show the user's current position. When the selected level of scale is not the entire body, a little body appears attached to the lower left portion of the WIM. This gives reference to where the user is within the body.

Also, if the selected scale in the WIM is not the same as the users' current scale, two arrows appear. The one attached to the lower left part of the WIM points to the users' current scale, relative to the selected scale in the WIM. The other arrow is attached to the hand, and points to the position in the VE of the selected scale in the MSWIM. Figure 3 shows both arrows and the reference body.

Table 1 gives a summary of the types and quality of information provided by the MSWIM technique.

5.3 HiSMap Technique

The Hierarchically-Structured Map (HiSMap) technique is based on the idea of showing the entire hierarchy structure formed by the levels of scale, so that users can view and select any level of scale at anytime. Figure 4 shows this idea implemented, with several icons connected by blue lines over the virtual tablet. Each icon represents a specific level of scale, and the lines connect nested levels of scale. The rows in which these icons are located represent how many scales nest the level of scale that is illustrated by the icon.

If the user moves the virtual hand and touches the icons, the selected scale changes to the one that is being touched. In Figure 4, the ribosome is the selected scale, so it is represented by its 3D model. As the icon is touched, it becomes bigger than the other

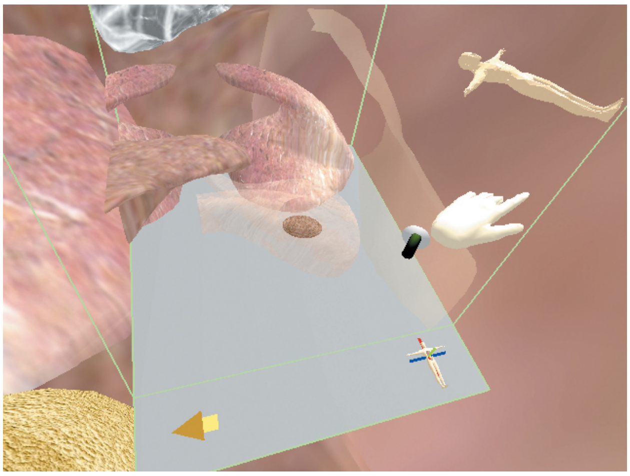

Figure 3: Arrows indicating the position in space (green) and the miniature (yellow) of the selected scale in the miniature and the users' current scale, respectively, plus the body that serves as a reference when the selected scale is not the entire body.

icons. Also, not only does it become highlighted, but the organ where the icon is becomes highlighted as well. Whenever users are not touching or selecting an icon, their current level of scale in the hierarchy will be the selected scale.

In order to keep a level of scale selected even when it is not being touched, users have to press the selection button. Doing this will freeze the hierarchy at the stage it was when they were touching the icon. If users touch other levels of scale in the hierarchy to see what they are, they do not grow or turn into 3d models, but a red box highlights them and their text description is attached to them. This means that, after freezing the hierarchy, the selected scale will not be updated as users touch the icons.

Figure 4 shows the body turned into an icon and a red line connecting the body to the selected scale. This means that the body is on the path to be followed to get to the selected scale. In addition to this, a blinking red arrow appears right above the body icon. This arrow indicates that the body is the user's current position in the hierarchy.

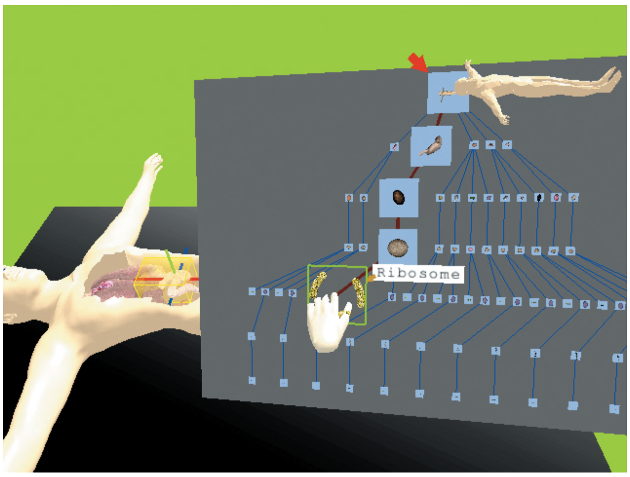

Figure 4: The level of scale and its icon representation being highlighted when touched.

To travel using this technique, users just have to select the scale to which they want to travel and press the travel button. Once the button is pressed, the tablet disappears and users start traveling to the selected scale, just like with the MSWIM technique.

Table 1 gives a summary of the types and quality of information provided by the HiSMap technique.

6 User Study

To evaluate the usability and performance of the techniques we designed, we carried out an experiment. The goal of this experiment was to evaluate the effectiveness of MSWIM and HiSMap in comparison to the baseline techniques developed by Kopper. We wished to investigate whether users could make use of the spatial and hierarchical wayfinding information provided by our techniques to navigate efficiently through an MSVE, and to verify the various types of information needed for different wayfinding tasks.

The following hypotheses were made:

H1) providing spatial information helps users improve performance in spatial orientation tasks;

H2) providing hierarchical information helps users perform better on naïve search tasks, as users just have to search for a specific level of scale in one hierarchical level;

H3) providing both hierarchical and spatial information helps users build up more survey knowledge.

Although we performed this experiment in the context of the anatomy MSVE, our hypotheses are not specific to this application, and we designed the experimental tasks to be representative of generic tasks that need to be performed in any MSVE. Thus, we feel that the results can be generalized to other MSVE applications.

6.1 Experimental Design

We adopted a four conditions between-subjects design. We denote the four conditions as Target+Steering, HiSMap, MSWIM and HiSMap+MSWIM.

In the Target+Steering condition, users only had access to the baseline techniques. This was the control group, in which little to no spatial or hierarchical information was provided. In the HiSMap condition, users could only use the HiSMap technique. In the MSWIM condition, users could only use the MSWIM technique. The HiSMap+MSWIM condition was the one in which the HiSMap and the MSWIM techniques are combined. Users could quickly change between one and the other, by just pressing a button.

Participants performed five different types of tasks, each representing one kind of information identified and provided by our techniques. Tasks required the use of spatial and hierarchical information, and concerned the hypotheses made. We designed three tasks for each type, leading to fifteen trials. Participants completed the trials in the same order, independently of the condition. The task types are described in Table 2, together with what was measured with them, an example and which hypotheses they tested.

The time spent, total distance traveled using the steering technique and the visited levels of scale were the dependent variables for the first four tasks. The errors made were considered as dependent variable for the fifth task type. In the case of the number of visited levels of scale, we considered all the levels of scale that users passed through to complete the task. That is because users in the Target+Steering always had to explicitly select levels of scale (either using target or steering techniques) to get to the one they wanted.

6.2 Apparatus

Throughout our experiment, a Macbook Pro with an nVidia geForce 8600gt graphics card was used, running Mac OS X. The application and the techniques were developed using C++ with the library SmallVR [12] for scene graph operations and OpenGL for rendering. A Virtual Research V8 head-mounted display with 640x480 resolution for each eye and a 60-degree diagonal FOV was used for visualization of the virtual world, and its position was tracked using an Intersense IS-900 6DOF tracker. A handheld tablet was used as a physical prop to the virtual tablet, and its position and orientation was also tracked. The tablet was designed to be held by the left hand, so only right-handed people could participate in our formal study. The device that contains the buttons and the joystick is a wand, and it is mapped to the virtual hand. The wand was used to interact with the techniques.

6.3 Procedure

Firstly, before participating in the experiment, users watched a video explaining how the technique they would use works. Before they began the experiment, users were asked to confirm if they were right handed, to read the informed consent form and to fill out a background survey questionnaire.

The first part of the experiment was a practice session, in which users were guided through all the features of the techniques they were using. In the next step, users completed fifteen trials (three of each type). After finishing a trial, users were asked to rate the ease of accomplishing it. After the completion of a set of tasks, users were given a five-minute break. Upon completion of all sets of tasks, users were interviewed.

6.4 Participants

Subjects were recruited from our university campus. Twenty-four subjects (9 female), aged 20 to 52, participated in the study, 6 participants for each group. All subjects had normal or corrected-to-normal vision and were right-handed. Users were intermediate to experienced computer users, 9 of whom having previous experience with multiscale interfaces and 6 with VR devices and applications. We balanced the groups so that each had at least 2 participants experienced with multiscale interfaces and 1 participant experienced with VR interfaces. None of the participants were members of our research group.

6.5 Results

Results presented in this section are the sum of the performance for the second and third evaluation trials. The performance on the first trial may be used for learning effects analysis in the future.

6.5.1 Time

Figure 5 illustrates the overall results of our experiment with respect to average task completion time for the naïve search task. This task tests the hypothesis H2, which claims that providing hierarchical information helps users to perform better on naïve search tasks. The Target+Steering condition resulted in the worst task performance, and the conditions with the HiSMap technique were the best for the first task.

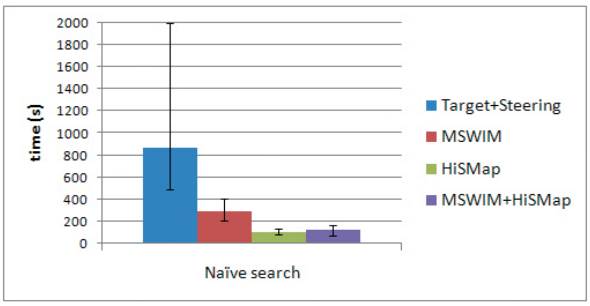

Figure 5: Average time spent for completing the naïve search task. The vertical lines represent standard deviation.

Table 2: Description of the within-subjects variable task types with the hypothesis tested by them, what was measured and examples.

Hypothesis tested	Type	What is being measured	Example
H1	**Relative position**: determine position relative to organs	Landmark information and knowledge relative to organs	*Are you closer to the liver or the heart?*
H1	**Steering**: use the steering technique to go to another scale at the same level	Capacity to determine the path to reach another level of scale at the same hierarchical level	*Use the steering technique (and do not use the travel button) to go to the red cell.*
H2	**Naïve search**: search for a specific level of scale	Hierarchical and spatial information about the level of scale	*Find the level of scale labeled as abnormal cell and travel there.*
H2	**Comparison**: compare levels of scale at the same hierarchical level	Knowledge about current position in the hierarchy	*Compare the abnormal cell with a normal cell and state the difference.*
H3	**Knowledge**: use of the spatial knowledge acquired (without the techniques and the devices)	Survey knowledge	*When you were inside the abnormal cell, which organ were you in? Which levels of scale would you pass to get there again?*

We performed a one-way ANOVA (alpha-level = 0.05) for all conditions and found a statistically significant effect ($F(3,20) = 9.18$, $p < 0.001$). A post-hoc Tukey HSD test was performed, and significant differences were found between MSWIM and Target+Steering ($p = 0.013$), HiSMap and Target+Steering ($p < 0.0001$), MSWIM+HiSMap and Target+Steering ($p < 0.0001$), MSWIM and HiSMap ($p < 0.001$) and MSWIM and MSWIM+HiSMap ($p < 0.01$) conditions. There was no statistically significant difference between the HiSMap and MSWIM+HiSMap conditions for the first task ($p = 0.764$).

As can be seen in Figure 6, the mean time for participants in the MSWIM condition was lower to perform the relative position task. This task tests the hypothesis H1, which claims that providing spatial information helps users improve performance on spatial orientation tasks.

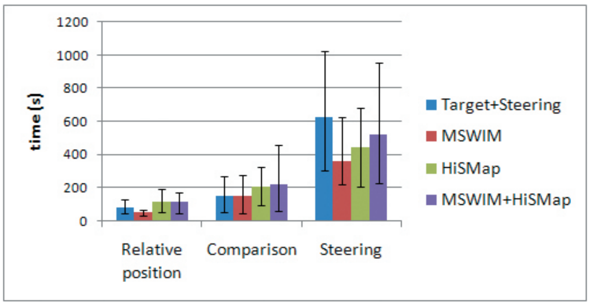

Figure 6: Average time spent for completing the relative position, comparison and steering tasks. The vertical lines represent standard deviation.

Again, we performed a one-way ANOVA (alpha-level = 0.05) for this task and found a statistically significant effect ($F(3,20) = 3.87$, $p = 0.025$). We also performed a post-hoc Tukey HSD test and found that the MSWIM is statistically better than HiSMap ($p = 0.036$).

We have not found any statistically significant differences between the conditions for the comparison task, which tests hypothesis H2, and the steering task, which tests hypothesis H1. Figure 6 shows that the means and variances of time spent for all conditions in these tasks were very similar, and does not support hypotheses H1 and H2.

6.5.2 Distance

Figure 7 illustrates the overall results of our experiment with respect to average distance covered using the steering technique for the naïve search and steering tasks. The distance is represented as a unit independent of the level of scale for movement (e.g.: if the user walks one step forward in the current scale, we consider this as one step).

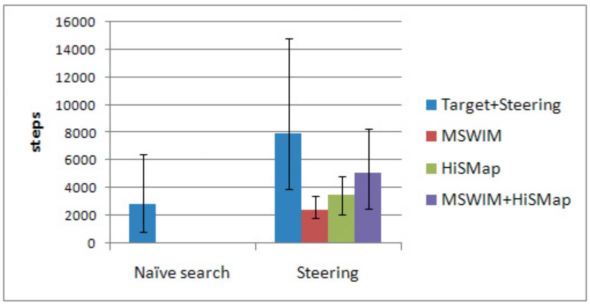

Figure 7: Average distance covered for completing the naïve search and steering tasks. The vertical lines represent standard deviation.

As can be seen, for the naïve search task, Target+Steering condition resulted in an elevated use of the steering technique. The comparison and relative position tasks were not taken into account, as users tended to have little to no use for the Steering technique when performing these tasks.

A one-way ANOVA was performed for the steering task, and we found a statistically significant effect ($F(3,20) = 5.55$, $p = 0.006$). For detecting differences between techniques, we performed a post-hoc Tukey HSD test, and found that participants in the MSWIM ($p = 0.006$) and HiSMap ($p = 0.026$) conditions performed statistically better than those in the Target+Steering condition.

6.5.3 Visited Levels of Scale

Figure 8 illustrates the overall results of our experiment with respect to average levels of scale visited for the naïve search and steering tasks and Figure 9 for relative position and comparison tasks.

We applied a one-way ANOVA for all conditions and found a statistically significant effect for the naïve search task ($F(3,20) = 17.67$, $p < 0.001$). We also performed a post-hoc Tukey HSD test, and found significant differences between MSWIM and Target+Steering ($p < 0.001$), HiSMap and Target+Steering ($p < 0.001$) and MSWIM+HiSMap and Target+Steering ($p < 0.001$) conditions.

For relative position, comparison and steering tasks, participants in the MSWIM conditions performed better than others. A one-way ANOVA for relative position and steering tasks showed statistically significant effects ($F(3,20) = 3.18$, $p = 0.046$ for the relative position

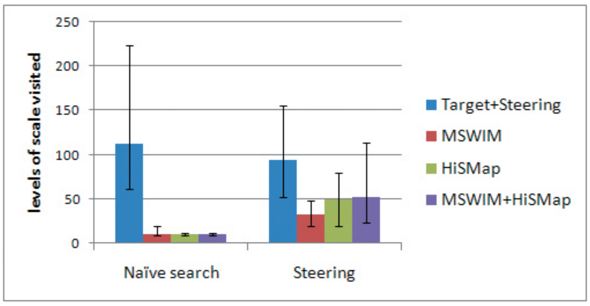

Figure 8: Average levels of scale visited for completing the naïve search and steering tasks. The vertical lines represent standard deviation.

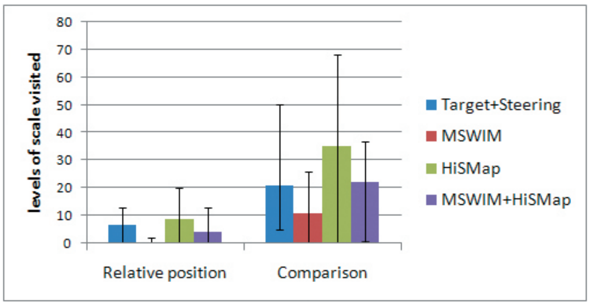

Figure 9: Average levels of scale visited for completing the relative position and comparison tasks. The vertical lines represent standard deviation.

task and F(3,20) = 4.41, p = 0.016 for the steering task). A post-hoc Tukey HSD test presented differences between HiSMap and MSWIM conditions for the relative position task (p = 0.035) and MSWIM and Target+Steering for the steering task. Performances in comparison task presented no statistically significant differences between the developed techniques and the Target+Steering conditions.

6.5.4 Number of Errors

Figure 10 shows the results for the knowledge task with respect to the average number of errors. This was the only metric for this task, as users had to give verbal answers and were not allowed to use the techniques or even look around the VE. This task tests hypothesis H3, which claims that providing both spatial and hierarchical information helps users to build up more survey knowledge.

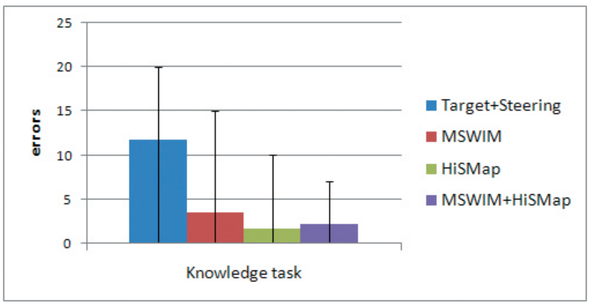

Figure 10: Average number of errors for completing the knowledge task. The vertical lines represent standard deviation.

A one-way ANOVA was performed and presented statistically significant differences (F(3,20) = 4.71, p = 0.012). A post-hoc Tukey HSD test confirmed the differences between HiSMap and Target+Steering (p = 0.018) and MSWIM+HiSMap and Target+Steering (p = 0.026) conditions. No statistically significant difference was found between the developed techniques.

6.5.5 Subjective Ratings

For the naïve search task, while the mean rating for the Target+Steering condition was lower than all the others (4.38), the HiSMap condition presented the best results (8.83), not significantly different from the MSWIM+HiSMap condition (8.5). In the relative position task, participants in the MSWIM condition had the best results (8.4). For the comparison and steering tasks, the mean ratings for conditions with the developed techniques had higher scores than the Target+Steering condition.

A Friedman's test was performed to analyze the scores for each task. We found significant changes in scores for the MSWIM ($p < 0.02$) and HiSMap ($p < 0.03$) techniques in regard to the relative position task, with the rating being significantly increased as users repeated the task. Tests for the comparison task showed significant effects for Target+Steering ($p < 0.02$) and MSWIM($p < 0.04$) conditions with an increase in performance. For the steering task, the only condition that presented significant effects on ratings was HiSMap ($p < 0.02$).

7 Discussion

The results of the relative position task support hypothesis H1, as users that used the technique that provided spatial information performed much better than all the other conditions. In addition, participants in the MSWIM condition found the task easier to accomplish. Interestingly though, the mean time spent for this task with the HiSMap and MSWIM+HiSMap conditions was greater than the time spent by participants in the Target+Steering. Observing the subjective data and the actions performed by those users, it seems that they spent some time looking for the answer in the HiSMap technique. Only after not finding the answer there, did they start to think about how to approach the task. The fact that this happened even when users had the possibility of using the MSWIM technique may be because the HiSMap technique has fewer components and less amount of cognitive effort involved.

For the steering task, the distance covered plays the most important role, as the task is all about using the steering to get to a specific level of scale. In this task, as expected, the MSWIM condition did better than others, mainly because it provides spatial localization information, and not just abstract information like in the HiSMap condition. Interestingly, participants in the MSWIM+HiSMap condition did not perform as well as when they were utilized separately and presented no statistically significant effects on the distance covered by users. We think this happened because of the high cognitive effort needed for learning and using both techniques at the same time. The results for the number of visited levels of scale were similar, being MSWIM the only condition with statistically better results than Target+Steering. Results for the subjective ratings show no significant differences between the conditions with the developed techniques. This supports the hypothesis H1.

The results for the naïve search task support hypothesis H2, because participants that had hierarchical information performed significantly better than those who had not. The time spent for doing the task was much less than with the control condition while not having to move at all. The number of levels of scale visited for this task was really low and near the ideal number for all conditions except the control one. This was already expected for the HiSMap and MSWIM+HiSMap conditions because the way that the techniques were designed allows users to look for the level of scale they desire without changing their current level of scale. Subjective ratings for this task are consistent with the results, as participants in the HiSMap condition presented the best scores. In the

Target+Steering condition, participants had to go to every level of scale until they found the one they were looking for.

It is interesting to notice that participants in the MSWIM condition performed much better than the Target+Steering condition, even though they had to use the same strategy. In order to discover why this happened, we performed an analysis on the number of levels of scale selected using the MSWIM technique, and compared this to the levels of scale visited by participants in the Target+Steering technique. The averages for both naïve search and steering tasks are different, and participants in the MSWIM condition had to look into fewer levels of scale than those in the Target+Steering condition.

A one-way ANOVA was performed to compare them, and we found significant differences for the steering task ($F(1,10) = 8.31$, $p = 0.016$). This means that changing the actual user scale had an effect on how many scales the user would have to visit to find the one that she was looking for. This may seem strange, but looking at the list of visited scales of participants in the Target+Steering and MSWIM conditions, we noticed that participants in the Target+Steering condition seemed to forget the levels of scale they had already checked, entering the same levels of scale several times.

Surprisingly, participants who had only the HiSMap technique performed worse than those in the Target+Steering condition in the relative position and comparison tasks, in terms of visited levels of scale. In the case of the relative position task, this may have happened, as commented by some users, because they expected to have the answer they were looking for in the technique, even after traveling and getting in or out of the level of scale to which they wanted to go or examine. For the comparison task though, only one of the participants in the HiSMap condition had the idea of looking at the 3D model that represented the level of scale in the technique. All participants seemed to avoid using the steering technique in finding the differences in the levels of scale, sometimes going in and out of the same level of scale by selecting it with the HiSMap technique.

The only statistically significant result of the comparison task is that those in the MSWIM condition performed better than those in the HiSMap condition, regarding the number of visited levels of scale. This happened because users in the HiSMap condition just had to find a level of scale in the same hierarchical level, and the path to get to that level was not significant. In the case of the participants in the MSWIM, it was always easier to go by the shortest path, as it would take less time to select the level of scale. Subjective ratings for the conditions with the developed techniques had better scores than Target+Steering, but there were no significant differences between them. Results for this task does not support hypothesis H2.

Results for the number of errors in the knowledge task do not support hypothesis H3, as there were no significant differences between the MSWIM+HiSMap and other conditions with the developed techniques. MSWIM, HiSMap and MSWIM+HiSMap conditions presented very similar results, but only participants in the conditions with the HiSMap technique had statistically better results than those in Target+Steering.

8 Conclusions and Future Work

This work presents the conception of wayfinding aids and associated travel techniques, developed specifically for MSVEs. Our contributions include the identification and classification of wayfinding information needed for travel in MSVEs and two interaction techniques that combine travel and wayfinding aids.

In addition, we also found that hierarchical information helps users to perform naïve search tasks better, while spatial information helps users more in spatial localization and orientation tasks. Another interesting finding is that allowing users to search for a specific level of scale without the need of changing their own scale has positive effects on performance.

For future work, we suggest the improvement of the developed techniques based on users' feedback, as well as the use of the information to design and develop new techniques. One interesting approach would be to combine both spatial and hierarchical information in a single technique. We also hope to evaluate our techniques in different application contexts and to develop navigation techniques that support exocentric viewing in MSVEs.

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