

Design and Evaluation of Navigation Techniques for Multiscale Virtual Environments

Regis Kopper*
Faculdade de Informática
PUCRS, Brazil

Tao Ni†
Dept. of Computer Science
Virginia Tech, USA

Doug A. Bowman‡
Dept. of Computer Science
Virginia Tech, USA

Marcio Pinho§
Faculdade de Informática
PUCRS, Brazil

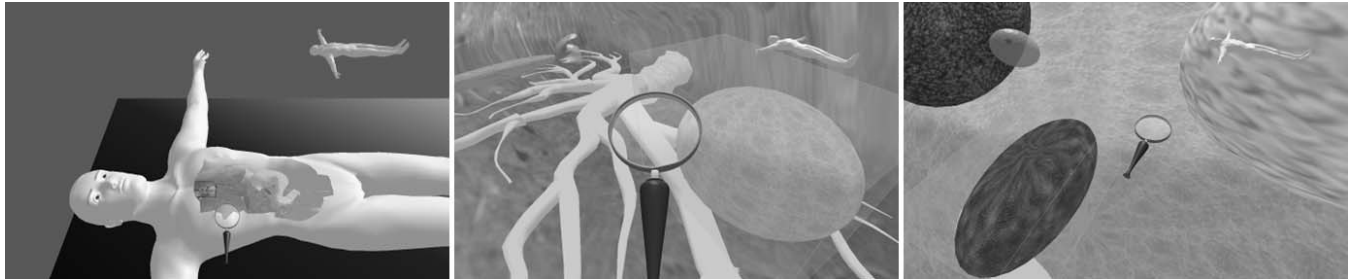


Figure 1: MSVE example: body scale, lung scale and a third level of scale. Note that the virtual magnifier is at a compatible size at all scales.

ABSTRACT

The design of virtual environments for applications that have several levels of scale has not been deeply addressed. In particular, navigation in such environments is a significant problem. This paper describes the design and evaluation of two navigation techniques for multiscale virtual environments (MSVEs). Issues such as spatial orientation and understanding were addressed in the design process of the navigation techniques. The evaluation of the techniques was done with two experimental and two control groups. The results show that the techniques we designed were significantly better than the control conditions with respect to the time for task completion and accuracy.

CR Categories: H.5.2 [Information Interfaces and Presentation]: User Interfaces; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality; I.3.7 [Computer Graphics]: Methodology and Techniques—Interaction Techniques

Keywords: multiscale virtual environments, interaction techniques, levels of scale, navigation, wayfinding aids, usability evaluation.

1 INTRODUCTION

Research in immersive virtual environments (VEs) has been concentrated mostly on the development of applications, interaction techniques and visualization tools for single-scale environments, where the user can experience the entire environment without the need to scale himself or the environment. In our work, we have been focusing on a type of VEs that have been only shallowly explored: Multiscale Virtual Environments (MSVEs). MSVEs [17] contain several hierarchical levels of scale in the same environment.

*e-mail: rkopper@inf.pucrs.br

†e-mail: nitao@vt.edu

‡e-mail: bowman@vt.edu

§e-mail: pinho@inf.pucrs.br

IEEE Virtual Reality 2006
March 25 - 29, Alexandria, Virginia, USA
1-4244-0224-7/06/\$20.00 ©2006 IEEE

In other words, smaller scales are nested within larger scales. To interact with MSVEs, the size of the user at any location must be compatible with the scale at that location. Apart from scaling the user appropriately, MSVEs must address other issues, such as how to tell the user which objects of the environment are levels of scale (LoS) objects and how to make it easy for the user to travel between different LoS while maintaining spatial orientation and understanding.

MSVEs are VEs that contain relevant information about different LoS. For a user to be able to interact effectively in MSVEs, it is important that the user is able to go back and forth among the LoS of the environment. This paper describes the design and evaluation of navigation techniques to make it possible for any user to navigate through different levels of scale in MSVEs. Our design goal for these techniques was to afford intuitive interaction at different LoS by automatically scaling the user to a comfortable size.

In our everyday lives, it is possible to find several situations that could be enhanced by MSVEs. In education, a MSVE could be used to enable students to see several levels of scale of the object of their study. For example, in medical education an MSVE could give users the ability to see the entire human anatomy in all its scales in the same environment, giving the student spatial and scale information that would not be possible if each level of scale was presented separately. The medical student could keep track of relationships between an organ and its inner parts, the inner parts of an organ and the tissue that forms it, the composition of a tissue and so forth down to maybe even the subatomic level.

Another example of a multiscale environment can be found in the cosmos, where the whole universe can be seen as the top scale and each galaxy as a lower LoS. Inside the galaxy the planetary systems could be seen as lower levels, one planet as a LoS inside a system and a continent as a LoS of some planet.

Thus, the study of multiscale navigation techniques was motivated by the lack of such techniques and the number of applications that could benefit from MSVEs.

The paper is organized as follows. Section 2 presents a review of previous work relevant to the research presented in this paper. Section 3 defines MSVEs and explains how we designed and developed navigation techniques to make travel among multiple LoS possible. Section 4 presents our evaluation of these techniques, and section 5 contains the results and discussion of the evaluation. Finally, sec-

tion 6 presents the conclusions of this work and gives directions for future research on this topic.

2 RELATED WORK

Multiscale interfaces were introduced by Perlin and Fox [11] as zoomable interfaces defined in an infinite two-dimensional information plane called Pad. This approach uses an infinite shared desktop with portals or magnifying glasses that show contextual information according to what part of the information plane is seen. For example, a calendar application will show only the years if the information plane is seen from a distance. When zooming in, the user will see the months of a small number of years, and zooming further in the days will appear. This kind of context-related information display is the same we use for MSVE levels of scale. Bederson and Hollan [1] used the concept of Pad to develop Pad++, which is a system to explore interfaces for information visualization in complex information-intensive domains. Both Pad and Pad++ were designed for two-dimensional interfaces; however, most of the concepts can be extended to three-dimensional immersive environments.

Furnas and Bederson [4] have developed a formalism called space-scale diagrams for describing multiscale interfaces. They are 3D diagrams extending a 2D image. The diagram has the shape of an upside down pyramid with several layers, each of which represents one level of scale of that image.

Working in different scales in VEs is a problem that has been addressed in several different ways. Zhang [16] describes how MSVEs are important to help people deal with multiscale structures in virtual worlds. By changing scale, the user is able to identify how the structures from different scales relate to each other and thus gain a better comprehension of the environment.

As a way of enabling the manipulation of large-scale objects and navigation to far away places, Pierce *et al.* [12] proposed the image plane interaction techniques. They consist of selecting objects that are within the user's view but not within arm's reach. The user selects objects by framing or occluding them with the hands. Then, it is possible to either navigate relative to the selected object or to manipulate it. With this technique it is possible to manipulate very large objects, like a house that is at distance, or to travel large distances by selecting a faraway landmark.

A similar technique for working in different scales in VEs is scaled-world grabbing [9]. This technique consists of selecting objects that are at a distance from the user, bringing them towards the user, and scaling them to fit in the user's hand. This way, it is easy to manipulate very large objects. When the manipulation is completed, the object is released and sent back to its original position.

The World in Miniature (WIM) technique is a widely-used technique for navigation and manipulation in VEs at different scales. The technique, as described by Stoakley *et al.* [15], consists of a hand held miniature of the world where the user can select the objects in the miniature and manipulate them. Also, the user can change his/her position in the miniature and will be sent to the selected position. Several extensions have been made to the WIM technique, such as showing the user position in the miniature in order to maintain spatial orientation [10] and a step WIM for hands-free navigation [5].

Zhang and Furnas [17] explore the use of 3D multiscale environments in collaborative VEs, in which the users can change their own scale (e.g. giant or ant scale), and are able to manipulate the environment as well as interact with users at the same scale. In the same paper, the authors present scale-based semantic representations. This means that an object's representation changes according to how close it is to the user, showing its inner composition for example.

Our research specifically addresses the navigation requirements

of MSVEs. Navigation has been described as consisting of two components: travel (the task of moving from one location to another) and wayfinding (the task of acquiring and using spatial knowledge) [2]. Many interaction techniques for travel [e.g. [8]] and many wayfinding aids [e.g. [3]] have been designed for VEs, but very few have addressed the requirements of multiscale navigation specifically. Our work extends the target-based and steering-based categories of travel techniques [2], and also implements aids for spatial orientation in MSVEs.

In the related work perhaps most similar to our own, Pierce and Pausch [13] have created an interface for large-scale virtual environments that consists of a combination of visible landmarks and place representations. Visible landmarks are landmarks strategically placed in the VE that give the user the opportunity to see objects that identify very faraway places. The visible landmarks go beyond typical landmarks that only help users to build their cognitive map, because they are moved and resized to be always visible by the user, no matter how far the user is from the actual place represented by the landmark. Further, the user can select a landmark using the image plane technique to travel directly or relatively to the desired place. The visible landmarks represent places that are hierarchically defined. The user can see landmarks for places that are in the same branch of the hierarchy as his/her current place and for places that are in the same level as the node that is the parent of the place where the user is. By organizing the space as a hierarchy of places, it is easier for users to maintain spatial orientation even when working in a very large VE and traveling very great distances.

We used the ideas of visible landmarks and place representations to develop our MSVE navigation techniques, but we had to change the original techniques to suit our needs. Because many MSVEs are cluttered environments that contain relevant information at several levels of scale, we had to find a way of showing landmarks for the places, or levels of scale in our case, in a way that wouldn't visually pollute the environment. The other limitation of [13] is that the place representations represent only planar areas, like terrains, and only the leaves of the place hierarchy can be visited. In our case, any node of the hierarchy may be a LoS that is reachable, so that a user can start at the root of the hierarchy and reach all its nodes. To address these problems, our techniques are based on a magnifying glass metaphor (section 3.1), so that the landmarks that show the locations of lower levels of scale are seen only through the glass.

3 MSVE NAVIGATION TECHNIQUES

The MSVE concept can be compared to the idea of Level of Detail (LoD) [7] in the sense that some parts of the environment may display more detail when they are approached. In LoD, the geometry of the objects is determined according to the user's point of view, showing the objects that are closer to the user in more detail, usually for performance purposes.

In MSVEs, the use of LoS is focused on the semantic meaning of the scales in the VE. While LoD changes the external appearance of an object, LoS defines more detail inside an object or location, with a whole new geometry that makes each LoS of an MSVE a complete working environment.

Another way to distinguish LoS from LoD is that in LoS not only is the appearance of the object altered, but also the user travels into the object, and has his/her own scale changed. Also, LoD techniques "hide" the existence of the levels from the user, trying to make the transitions as seamless as possible. In MSVEs, however, the system explicitly presents information about the existence of LoS in order to give the user the possibility to explore them.

Most existing 3D navigation techniques do not address the issue of user scale. Often, the user can set the travel speed, but that is not the same as changing size. Our approach takes into consideration that the user should be dynamically rescaled to fit inside the LoS

and see it as the whole working environment (Figure 1).

To calculate how much the user should be scaled when entering a LoS, we use a function of the volume of the object that contains the LoS. We define the scale factor to be the cube root of the ratio between the volume of the last LoS and the new one (Equation 1).

$$ScaleFactor = \sqrt[3]{\frac{Volume_{NewLoS}}{Volume_{LastLoS}}} \quad (1)$$

We used a ratio between the volumes to calculate the scale factor because the LoS are three dimensional environments and so their size is best described by their volume. The reason for the cube root is that we need to get a scalar (one-dimensional) value from a volumetric (three-dimensional) ratio.

In MSVEs, the size of the objects can vary greatly, and so the distance between them and the user varies greatly as well. For example, in our anatomy application, when the user is at top scale, the distances are on the order of meters. However, when the user is inside an organ, the distances will be more on the order of centimeters or millimeters. Thus, we have to adjust the near and far clipping planes to the user scale. This is done by multiplying the near and the far values of the view frustum by the user scale factor. The field of view (FOV) can match the display device FOV and doesn't need to change with the change of user scale (Figure 2).

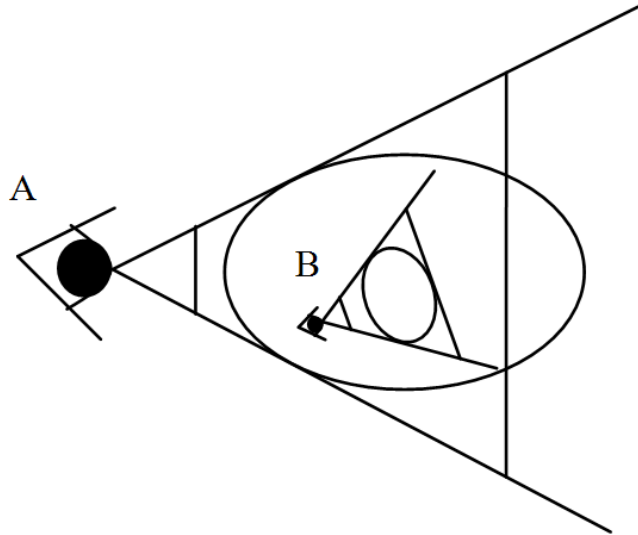


Figure 2: a) the view frustum of a higher LoS; b) the view frustum of a lower LoS. The ratio between the near and far clipping planes is constant.

3.1 Magnifying Glass

The tool we chose to navigate through different LoS in an MSVE was a magnifying glass (Figure 3). We used this metaphor because the LoS are magnifications of the object we want to explore further. The magnifier has a semi-transparent glass through which some information about the LoS is shown.

The first purpose of the magnifying glass is to show the user what objects in the environment are lower LoS. When the user looks through the magnifier, all the objects that can be further explored are shown with a wireframe bounding box around them (Figure 4). The object whose center is closest to the center of the magnifying glass has a golden bounding box, meaning that this is the LoS to which the user will be sent if she gives the scale down command (Section 3.2).



Figure 3: Magnifying glass.

We have developed two techniques for multiscale navigation: target-based and steering-based. Those techniques are detailed in the next subsections.

3.2 Target-Based Multiscale Navigation

In our target-based multiscale navigation technique, the user is automatically moved from the current location to the center of the selected LoS object. This technique is appropriate for tasks in which the user has a goal to accomplish and wants it done quickly and efficiently.

The user selects the object he intends to explore more deeply with the magnifying glass and gives the scale down command (e.g. by pressing a button). The movement occurs by translating the user in a straight line defined by Equation 2 over the course of five seconds (Figure 5).

$$Vector = \overrightarrow{Center_{NextLoS} - Position_{LastLoS}} \quad (2)$$

During the transition, the navigation control is disabled to keep the user moving in the right direction.

Once the scale down command is given, the user is scaled to the appropriate size for the LoS he has selected. What actually changes is the travel speed, and the size and distance of the magnifying glass. Because the magnifier is now smaller but also closer to the user, and because during the transition navigation is disabled, there is no way for the user to perceive the change in his scale. To address this, a navigation aid was developed to help the user know that he is shrinking. This aid is detailed in section 3.4.

Once in a lower level of scale, the user can stay there, scale back up, or scale down further to a new LoS. To scale up, only a command such as the pressing of a scale up button is necessary, and to scale down the user repeats the procedure with the magnifying glass.

3.3 Steering-Based Multiscale Navigation

The other method of changing scale is by traveling in the direction of an LoS object and entering it. We designed this technique for exploratory multiscale navigation, where the time is not the most important factor. When traveling in the current LoS, whenever the

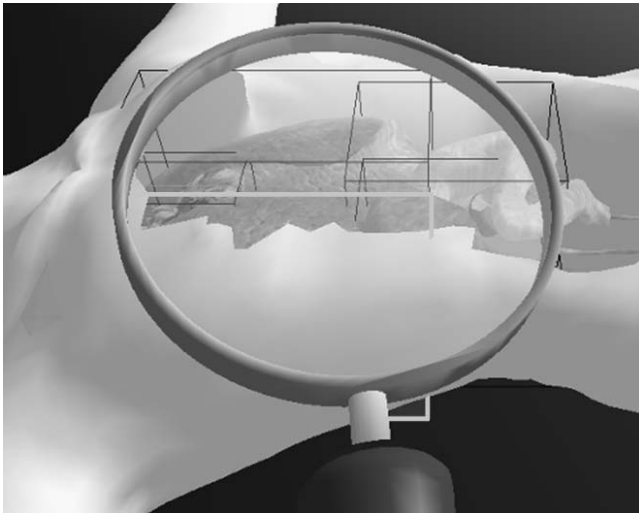


Figure 4: Levels of scale shown through the magnifying glass.

user flies into a lower LoS and stops inside it, she will be automatically scaled down to that LoS. The same thing happens in reverse. If the user flies out of a LoS, she will automatically be scaled up to the parent LoS.

Several issues had to be considered and discussed when we developed the steering-based technique. The idea was to use an intuitive travel technique, like flying, in such a way that whenever the user entered an LoS object she would automatically receive the scale factor of that LoS. The problem here was that sometimes the user would just be exploring the current LoS, but might be unintentionally scaled down when flying through a lower LoS, or up when flying outside of it. We resolved this problem by adding a constraint so that in order to be scaled down or up, the user now had to stop moving inside a lower or higher LoS. That way the user can fly freely through a level of scale, not having to worry about avoiding any LoS that could be in her way.

Another issue that we found during an exploratory study was that the user could accidentally move out of a LoS by leaning back (our system uses head tracking). Once he was out of the LoS, he would be scaled up and, consequently, move with a greater speed. Our first attempt to solve this problem used an outer shell that was the same shape of the LoS but 20% larger in volume. A user now wouldn't be scaled up simply by leaning backward. Still, his viewpoint would leave the level of scale, and the only thing that he would see when accidentally moving out of a LoS object would be its wall.

We then tried a second solution that proved to be the best one. We specified that the only means of scaling up would be through the explicit pressing of the scale up button or through flying, but not through a head movement captured by the tracker. Whenever the user reaches the boundary of the object that defines the LoS, the user's movement stalls and he can move only within the volume of the LoS. It could be claimed that this approach might produce a break in presence or at least feel strange to users. However, we found from observation that users didn't mind it, and even felt it fair enough that once they were inside a LoS, they could not move out of it by physical movements.

3.4 Multiscale Navigation Aids

The techniques described above are enough for the user to find and navigate through different scales in an MSVE. However, when continually changing scale, the user can get spatially disoriented, so we developed some orientation cues that help the user to maintain

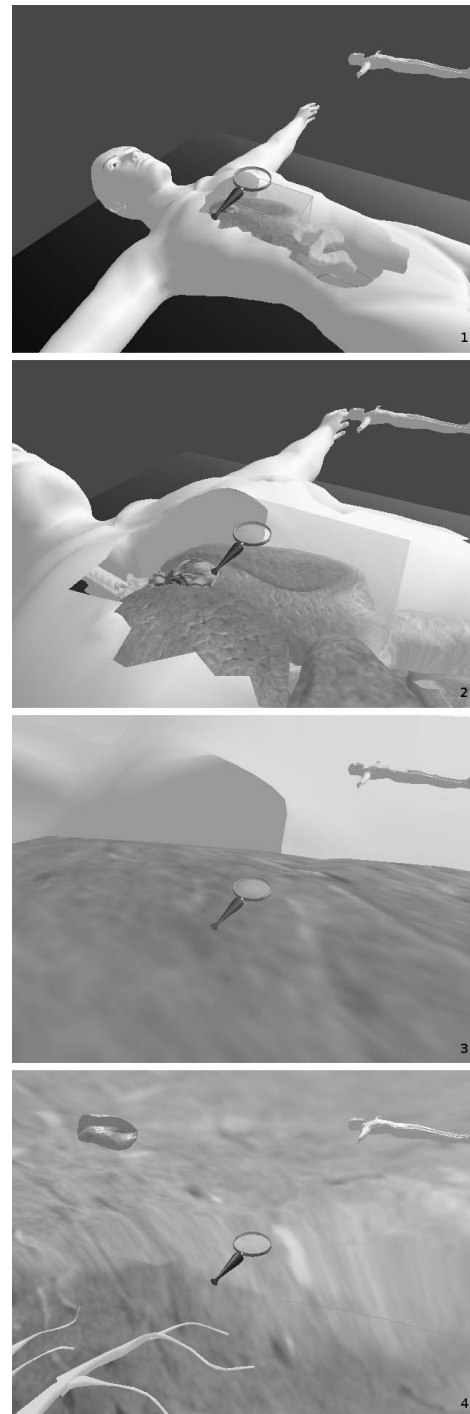


Figure 5: Four frames of the target-based scale change transition. From top to bottom: 1. The user is located at the top level of scale. She employs the magnifying glass widget to highlight an object with a lower level of scale. 2 and 3. The transition between two levels of scale is initiated via pushing a scale down button. The user then automatically traverses to the lower level of scale along a pre-computed course. Note that during the transition, the virtual navigation is disabled. 4. The user enters the selected object. An additional miniature object of the current level of scale is rendered at the upper left corner. The user is free to navigate in the current world, or push a scale up button to travel back.

spatial orientation and understanding even after several changes of scale.

A You-are-here (YAH) map [6] is a powerful tool for spatial knowledge acquisition. It combines a map with a YAH marker, which assists users in obtaining spatial awareness by providing the dynamically updated viewpoint position and/or orientation on the map [2]. It is also recognized that a map works better when aligned with the environment to avoid mental rotations [2]. We have been aware of these concepts for the development of the following cues to keep the user spatially oriented.

A *top scale*, which means the scale that encompasses all the other LoS of the MSVE, is always defined. For example, in the anatomical MSVE, the entire body is the top scale, and in an astronomical MSVE, the Milky Way could be defined as the top scale. In order for the user to keep track of her orientation in relation to the top scale, a miniature model of the top scale is always shown in the top right corner of the display, and its orientation is the same as the user's orientation (Figure 6b). The purpose of this visual cue, in addition to giving the user information about her global orientation, is to enable the user to know her position in relation to the neighbor LoS.

The other visual cue shown to the user is a miniature model of the current LoS. As with the top scale model, the current LoS model is oriented according to the user's orientation (Figure 6a). This miniature also shows a blinking dot that represents the user's position in this LoS. The purpose of this miniature, which is shown in the top left corner of the display, is to give the user information about where she is right now - in which LoS she is as well as her exact position in the current LoS.

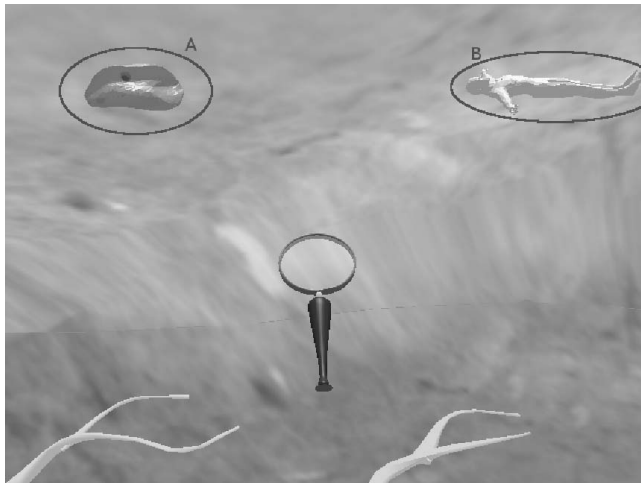


Figure 6: a) Miniature model of the current level of scale; b) Miniature model of the top scale.

A third visual cue was implemented but was not tested in the experiments. It was an object resembling a person that showed up in the lower left part of the display whenever a scale transition was taking place. If the user was scaling down, this object would start big and shrink in an animation, and if the user was scaling up, this object would start small and get bigger. This aid was intended to give the user the information that automatic scaling was taking place and represent the direction the user was scaling. Our informal study, however, showed that this cue was not only unnecessary but actually annoying to most users. Therefore, we decided to remove this aid for the formal experiment detailed below.

4 EXPERIMENT

To evaluate the usability of the interaction techniques, we conducted an evaluation. The goal of the evaluation was to compare different techniques through the collection of user performance data. We were especially interested in the time users take to navigate between scales with a certain technique, as well as the acquisition and maintenance of spatial orientation. We were mainly interested in two comparisons: first, the comparison of our techniques to more naïve multiscale navigation techniques, and second, the comparison of target-based and steering-based techniques.

4.1 Experiment Design

The study used a 2x2 (Scaling: automatic, manual x Navigation: target-based, steering-based) design, with 6 subjects assigned in each group (Table 1). The two experimental groups are target- and steering-based navigation combined with automatic scaling techniques, while the other two groups are taken as control groups in our experiment design and use a manual scaling technique.

Table 1: Experiment design.

	Target Based	Steering Based
Automatic	Task set 1	Task set 1
	Task set 2	Task set 2
Manual	Task set 1	Task set 1
	Task set 2	Task set 2

By manual scaling, we mean that users control their own scale (and indirectly, their travel speed). This certainly imposes greater cognitive load on the user, but also allows the user greater flexibility in choosing the scale that is most appropriate for his current task. In our control groups, the manual scaling was done by pressing two buttons on the input device, the upper for scaling up by 10% and the lower for scaling down by 10%.

Within a group, each user performed two sets of four tasks. The tasks in the two sets were of the same types and levels of complexity, and thus required similar amounts of effort to complete. This allowed us to investigate not only how users' task performance differs across the experimental and control groups, but also how different techniques affect the learning curve.

The tasks in each set consisted of two types. The first three were exploration and search tasks, in which the user was expected to navigate back and forth in various LoS and find objects with certain features. For example, "In the left lung, find the object that has four spheres inside." The fourth task in each set required the user to point in a certain direction (an orientation-based task). For instance, we might ask the user to point to the center of the head from their current location.

The between-subjects independent variables were Scaling and Navigation techniques, and the within-subjects independent variable was task set. Task completion time and the angle between the correct direction and the measured direction for the orientation-based task were taken as the dependent variables.

4.2 Research Hypotheses

Our research hypotheses were: 1. Users in experimental groups will outperform those in control groups. 2. Target-based multiscale navigation techniques will result in better task performance than steering-based techniques. 3. Users in control groups will take longer to learn the interaction techniques than those in experimental groups.

4.3 Environments and Apparatus

We created a multiscale human anatomy model as the experimental environment. Inside the body there are organs such as the heart and lung, which themselves contain lower LoS. For example, the user can explore the world inside the left lung, where there are additional objects that are at a smaller scale.

We used a Virtual Research V8 Head-Mounted Display (HMD) with 640x480 resolution and 60° diagonal field of view as the display device. The HMD was used in biocular (same image to both eyes) mode. The user's head and hand were tracked by InterSense IS-900 VET trackers. The handheld wand has a joystick and 5 buttons, two on the left, two on the right and one in the joystick. The software was written in C++ and OpenGL with the SmallVR toolkit [14].

For the target-based techniques, we mapped the magnifying glass to the wand so that the distance between the wand and the user matched the distance between the magnifier and the virtual user. To scale down, the subjects had to press the lower left button on the wand, and to scale up the upper right button was used.

For the steering-based setup, instead of the magnifying glass, the user had a virtual hand (Figure 7) and the travel was done using the wand's joystick. The travel technique was pointing-based, meaning that the direction of the movement when pressing the joystick forward was in the direction the wand was pointing. The joystick could also be pressed in other directions, like backward or sideways, allowing the user to back up or "strafe".



Figure 7: The virtual hand for the steering-based techniques.

To correct discrepancies between the user's physical and virtual hand locations, especially after user scaling, a reset button in the wand was defined. To reset the magnifier or virtual hand position, the user held the wand in front of his forehead and pressed the middle (joystick) button.

4.4 Procedures

Subjects were recruited on our university campus. 24 subjects (ages between 18 and 43), 12 females and 12 males, volunteered for the experiment, with 6 placed in each group. The gender distribution was even in all groups. Seven subjects were students in engineering disciplines, while the others were from non-engineering majors. Two out of 24 subjects were left-handed, and all of them had normal or corrected-to-normal vision. Two subjects ranked themselves as advanced computer users, and the others as intermediate users. Seven subjects had experience with VEs (e.g. HMD or CAVE). All participants completed the experiment.

Upon arrival, subjects filled in a background survey questionnaire, were given detailed instructions, and completed a training session. The training environment was very simple and composed only of spheres (Figure 8) but allowed users to practice navigating in an MSVE with their assigned navigation technique. We allowed as much time as each subject needed in the training environment so that he/she was able to act fluidly. Subjects then performed tasks in order and we measured task completion times. Subjects were free to take a break at any time, but no subject asked to stop in the middle of the tasks. After participants finished all tasks, they completed a post-experiment questionnaire and were thanked for their time and efforts. The questionnaire included subjective ratings of levels of difficulty to perform tasks, to navigate through LoS, and to maintain spatial orientation. The rating scales were Likert scales ranging from 1 (strongly disagree) to 7 (strongly agree). It also included free-form questions where subjects could make comments and suggestions.

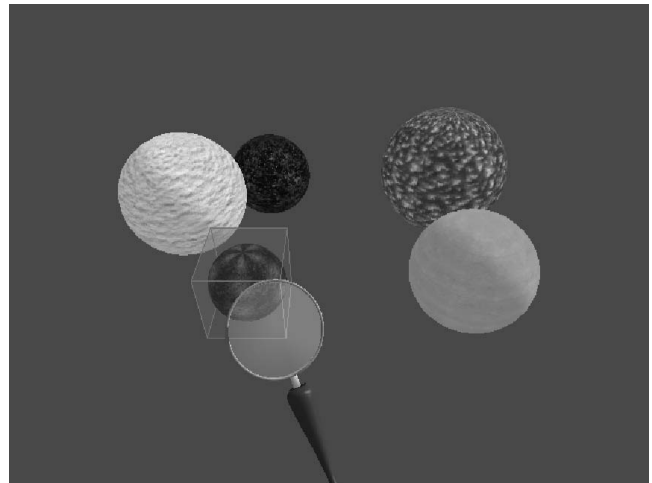


Figure 8: Training environment sphere world.

5 RESULTS AND DISCUSSION

5.1 Task Performance Data

Figure 9 illustrates the results of our experiment with respect to average task completion time. The mean time for the two experimental groups was 68.03s, while the mean time for the two control groups was 119.56s, which is about 43.1% higher. With automatic scaling enabled, subjects took much less time to navigate to the required location, which is consistent with our hypothesis 1. In addition, subjects with the target-based navigation technique (mean time = 77.58s) outperformed those with the steering-based navigation technique (mean time = 110.01s), consistent with hypothesis 2. The performance data was analyzed with a two-way analysis of variance (ANOVA). We found significant main effects of scaling technique ($F(1, 20)=13.84, p=0.0014$) and navigation technique ($F(1, 20)=11.74, p=0.0027$).

A significant interaction between the scaling and navigation factors was found as well ($F(3, 20)=7.80, p=0.0112$). This interaction can be explained by examining figure 9. With target-based navigation, automatic scaling yields far better performance than manual scaling. With steering-based navigation, however, the difference between automatic and manual scaling is much smaller. A post-hoc two-tailed t-test showed that with target-based navigation, there is a significant difference between the automatic and manual scaling techniques ($t(20)=-4.61, p=0.009$). However, no signifi-

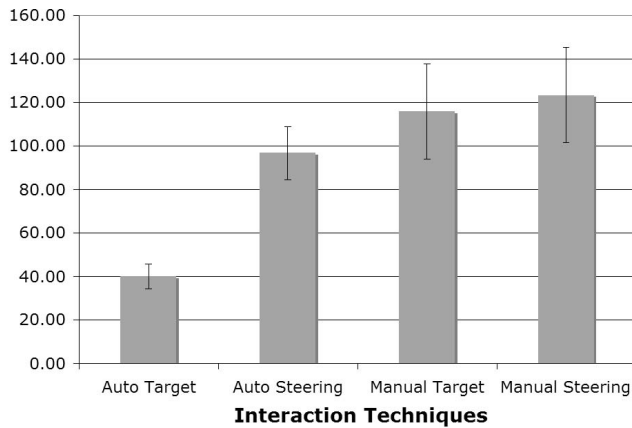


Figure 9: Overall average task performance.

cant difference existed between the scaling techniques when paired with steering-based navigation ($t(20)=-0.66$, $p=0.9121$). The target-based navigation technique was designed as a simpler method for navigating MSVEs, especially for novice VE users. In contrast, the steering-based technique required more proficiency with traditional flying-style VE navigation. As a result, we believe that the difference between the automatic and manual scaling techniques was a primary factor that affected task performance in target-based groups, but a secondary factor in steering-based groups. In other words, subjects in steering-based groups spent more effort in navigating than in scaling, hence weakening the effects of scaling techniques.

A similar trend emerged when we looked at the difference in task performance between the target and steering-based navigation techniques within the experimental (the first and second bars in Figure 9) and control groups (the third and fourth bars). That is, navigation technique had a significant effect on task completion time in the automatic scaling groups ($t(20)=4.40$, $p=0.0015$), but not in the manual groups ($t(20)=0.45$, $p=0.9691$). Our interpretation is that the manual scaling technique was so cognitively difficult that it acted as a major factor affecting users' performance in the control group, thus weakening the effect of navigation technique.

As we described above, the fourth task in each set was a pointing task designed to evaluate the effectiveness of the global and local navigation aids we designed. Since the navigation aids were present in all experimental conditions, we did not expect to find any significant differences in pointing accuracy due to navigation or scaling technique. The average pointing error overall was 55.29 degrees, ranging from 39.41 degrees to 89.89 degrees in the different conditions. This level of accuracy indicates that our navigation aids were effective in helping users maintain spatial orientation in general, but that they were not detailed enough to produce extremely high accuracy. As we expected, we found no significant differences between the conditions.

5.2 Learning Effects

As described in the previous section, we were interested in how quickly and easily users could learn to use the interaction techniques effectively. We did not observe any significant effect of interaction techniques on learning (Figure 10), although subjects achieved better performance in the second set (average task completion time 105.02s vs. 82.57s). We believe that most subjects understood the interaction techniques well in the training session, and practiced sufficiently before they performed tasks.

The performance of the second set is 35.25% better than that

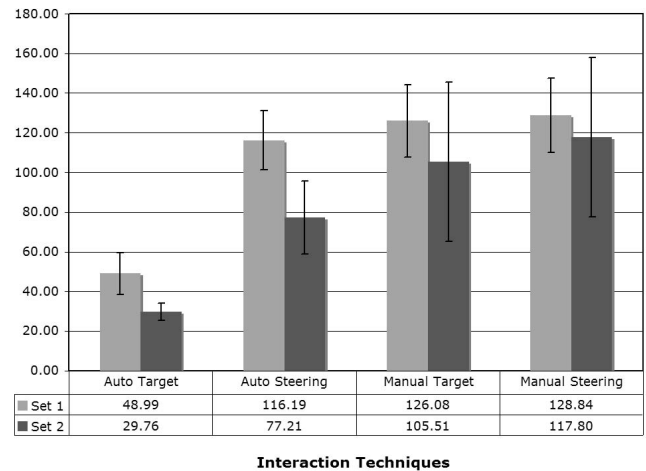


Figure 10: Average task performance between two sets.

of the first set in the experimental groups (82.59s vs. 53.48s), but only 12.4% better in the control groups (127.46s vs. 111.65s). In spite of the lack of statistical evidence, this is a trend indicating that it may take longer to achieve optimal performance with the interaction techniques in the automatic scaling groups, compared with those in the manual scaling groups. If this trend is real, it would contradict our hypothesis 3. More research is needed to understand this trend.

5.3 Subjective Ratings

The average questionnaire ratings with respect to overall level of difficulty, level of difficulty in navigating and level of difficulty in scaling judgment are illustrated in Figure 11. Lower ratings are better. A two-way ANOVA was performed to analyze the scores on each question.

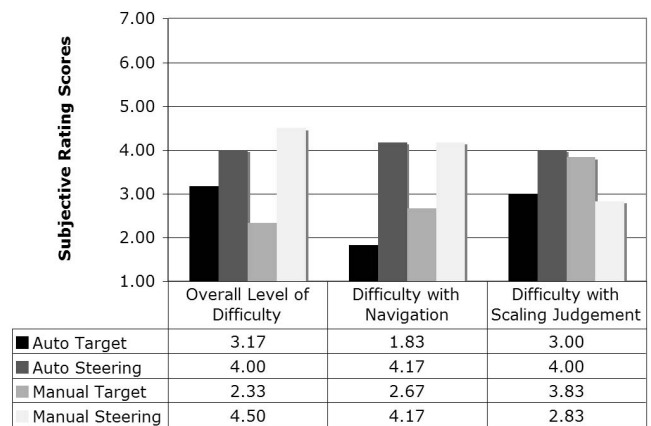


Figure 11: Subjective ratings. Lower scores are better.

We found significant effects of navigation technique for both the overall level of difficulty of task completion ($F(1, 20)=12.46$, $p=0.002$) and the difficulty of the navigation techniques ($F(1, 20)=17.06$, $p=0.0005$). This result is consistent with the comments of the subjects; most users commented on the ease-of-learning and ease-of-use of the magnifier tool.

We did not find, however, any significant effect of interaction techniques on the level of difficulty with scaling judgment. As a

matter of fact, the average score of this question is even slightly higher with automatic scaling (3.5 vs. 3.3).

6 CONCLUSIONS AND FUTURE WORK

We have presented the design and evaluation of navigation techniques for multiscale virtual environments. The results of our user study are encouraging and indicate that the techniques we developed are effective and usable. We found that automatic scaling was clearly more efficient than manual scaling. Target-based navigation also performed better than steering-based navigation, which is not surprising since target-based techniques are designed for specific goal-oriented tasks like those in our study. We wish to emphasize, however, that in a real MSVE application, the combination of both target-based and steering-based navigation, along with automatic scaling, would be the most effective and flexible way to support all types of navigation tasks.

In the future, we think that other navigation aids could be explored, such as the use of "gravity" with the steering-based technique (to pull the user toward potentially interesting LoS). This would be especially interesting for low-density environments such as planetary systems.

It is possible to combine these MSVE navigation techniques with other techniques for interacting (selecting, manipulating, creating) within the levels of scale, although we have not yet performed any research on this kind of integrated MSVE interface.

We have focused on a single environment and a small set of tasks in this work. Although we feel that our anatomical environment and tasks are representative of many MSVE applications, a larger number of applications and tasks should be evaluated to generalize our findings.

We concentrated our work on the design of interaction techniques for MSVEs, and didn't worry about performance issues. However, we're aware that complex MSVEs may contain a very large number of geometric objects. An important future research direction for MSVEs would be an investigation of how to optimize the display of geometry so that the system would not be overloaded by the rendering of geometry that is not visible to the user. One alternative would be to show only the geometry of the LoS that are immediately reachable by the user, and to do some dynamic switching of the rendered objects based on the current LoS.

7 ACKNOWLEDGEMENTS

This work was partially funded by the Brazilian National Science and Technology Development Council (CNPQ).

REFERENCES

- [1] Benjamin B. Bederson and James D. Hollan. Pad++: a zooming graphical interface for exploring alternate interface physics. In *UIST '94: Proceedings of the 7th annual ACM symposium on User interface software and technology*, pages 17–26, New York, NY, USA, 1994. ACM Press.
- [2] Doug A. Bowman, Ernst Kruijff, Joseph J. LaViola, Jr., and Ivan Poupyrev. *3D User Interfaces: Theory and Practice*. Addison Wesley Longman Publishing Co., Inc., Redwood City, CA, USA, 2004.

- [3] Rudolph P. Darken and John L. Sibert. Wayfinding strategies and behaviors in large virtual worlds. In *CHI '96: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 142–149, New York, NY, USA, 1996. ACM Press.
- [4] George W. Furnas and Benjamin B. Bederson. Space-scale diagrams: understanding multiscale interfaces. In *CHI '95: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 234–241, New York, NY, USA, 1995. ACM Press/Addison-Wesley Publishing Co.
- [5] Jr. Joseph J. LaViola, Daniel Acevedo Feliz, Daniel F. Keefe, and Robert C. Zeleznik. Hands-free multi-scale navigation in virtual environments. In *SI3D '01: Proceedings of the 2001 symposium on Interactive 3D graphics*, pages 9–15, New York, NY, USA, 2001. ACM Press.
- [6] M. Levine, I. Marchon, and G. Hanley. The placement and misplacement of you-are-here maps. *Environment and Behavior*, 16(2):139–157, 1984.
- [7] David Luebke, Benjamin Watson, Jonathan D. Cohen, Martin Reddy, and Amitabh Varshney. *Level of Detail for 3D Graphics*. Elsevier Science Inc., New York, NY, USA, 2002.
- [8] Mark R. Mine. Virtual environment interaction techniques. Technical report, Chapel Hill, NC, USA, 1995.
- [9] Mark R. Mine, Jr. Frederick P. Brooks, and Carlo H. Sequin. Moving objects in space: exploiting proprioception in virtual-environment interaction. In *SIGGRAPH '97: Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pages 19–26, New York, NY, USA, 1997. ACM Press/Addison-Wesley Publishing Co.
- [10] Randy Pausch, Tommy Burnette, Dan Brockway, and Michael E. Weiblen. Navigation and locomotion in virtual worlds via flight into hand-held miniatures. In *SIGGRAPH '95: Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 399–400, New York, NY, USA, 1995. ACM Press.
- [11] Ken Perlin and David Fox. Pad: an alternative approach to the computer interface. In *SIGGRAPH '93: Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, pages 57–64, New York, NY, USA, 1993. ACM Press.
- [12] Jeffrey S. Pierce, Andrew S. Forsberg, Matthew J. Conway, Seung Hong, Robert C. Zeleznik, and Mark R. Mine. Image plane interaction techniques in 3d immersive environments. In *SI3D '97: Proceedings of the 1997 symposium on Interactive 3D graphics*, pages 39–44., New York, NY, USA, 1997. ACM Press.
- [13] Jeffrey S. Pierce and Randy Pausch. Navigation with place representations and visible landmarks. In *VR '04: Proceedings of the IEEE Virtual Reality 2004 (VR'04)*, page 173, Washington, DC, USA, 2004. IEEE Computer Society.
- [14] Marcio S. Pinho. SmallVR: Uma ferramenta orientada a objetos para o desenvolvimento de aplicações de realidade virtual. In *Proceedings of Symposium on Virtual Reality '2002*, pages 329–340, Porto Alegre, RS, Brazil, 2002. SBC - Brazilian Computer Society.
- [15] Richard Stoakley, Matthew J. Conway, and Randy Pausch. Virtual reality on a wim: interactive worlds in miniature. In *CHI '95: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 265–272, New York, NY, USA, 1995. ACM Press/Addison-Wesley Publishing Co.
- [16] Xiaolong Zhang. Space and place in multiscale virtual environments. In *Space, Spatiality and Technology Workshop*, pages 31–38, 2003.
- [17] Xiaolong Zhang and George W. Furnas. Social interactions in multi-scale cves. In *CVE '02: Proceedings of the 4th international conference on Collaborative virtual environments*, pages 31–38, New York, NY, USA, 2002. ACM Press.



Figure 3: Magnifying glass.

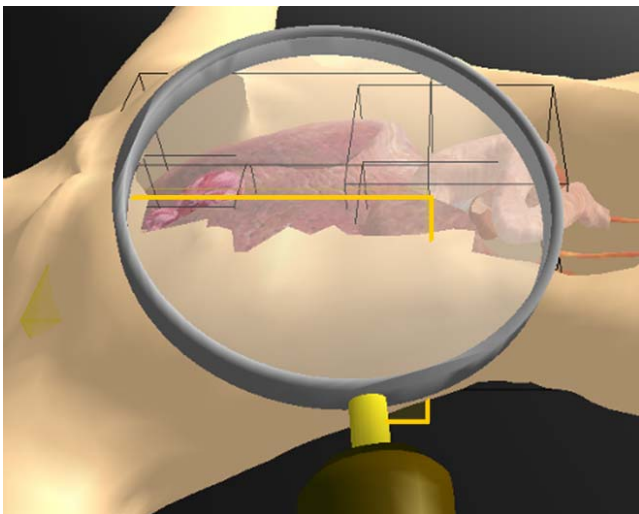


Figure 4: Levels of scale shown through the magnifying glass.

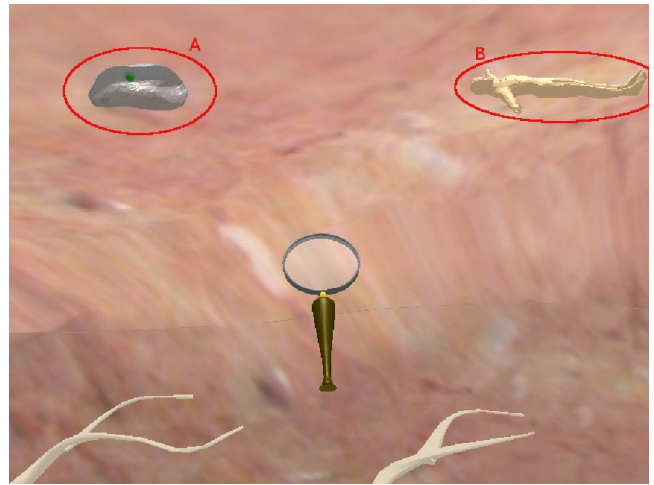


Figure 6: a) Miniature model of the current level of scale; b) Miniature model of the top scale.

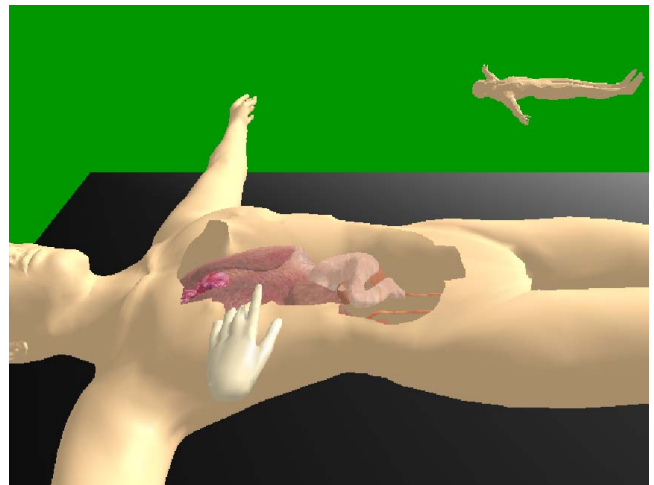


Figure 7: The virtual hand for the steering-based techniques.

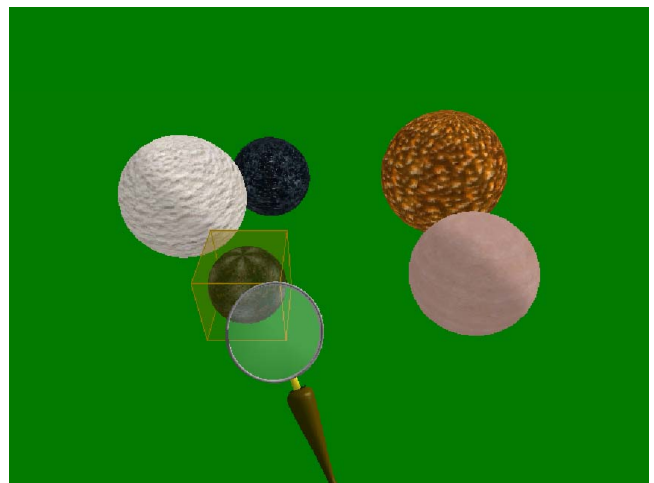


Figure 8: Training environment sphere world.