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ORIGINAL ARTICLE

Multiscale traveling: crossing the boundary between space and scale

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Abstract Adding multiscale interaction capabilities to 3D virtual environments may permit work with huge virtual worlds that might otherwise be too large to manage. Multiscale technology has shown potential to support user interactions. This paper reports an experimental study of two multiscale traveling techniques. Our results show that while allowing a flexible control on travel speed and accuracy is beneficial, directly traversing the space-scale could be a challenge for users, probably due to difficulties in perceiving scalable virtual space and executing scaling operations. The results suggest that more research is needed to improve the understanding of the coupling of space and scale in multiscale user interface and to harness the full potentials of multiscale traveling techniques.

Keywords Navigation · Multiscale · Virtual environments

1 Introduction

One of challenges in navigation in virtual environments is the balance of traveling speed and accuracy (Mackinlay et al. 1990). Various tools have been developed to help users reach a known destination quickly with high precision. For example, automatic traveling algorithms have been developed to move a user from one point to another without involving the user involved in travel control (Mackinlay et al. 1990). However, when using such system-driver tools, a user is led by the system, and is no longer an active explorer. Since J.J. Gibson's seminal work on the relationship between human activities and environments (Gibson 1979), the importance of active exploration to a good understanding of environments has been well recognized and studied (Bowman et al. 1997; Evans and Pezdek 1980). Recent studies show that using automatic navigation systems may make people less engaged with environments (Leshed et al. 2008; Parush et al. 2007). These results imply that there is a need for efficient and interactive traveling control in navigation.

One approach to addressing this need is to use multiscale techniques (Furnas and Bederson 1995). In 3D virtual environments that are equipped with multiscale tools, users can adjust their action domains when interacting with large structures that demonstrate various characteristics at different scale levels (Zhang and Furnas 2005). Dynamically changeable interaction scales in virtual environments provide users with opportunities to travel quickly and precisely by manipulating the scale factor of virtual space, or the relative size of space. Users can either execute scaling operations and space movements as two different actions, or combine them into one single action. By executing them separately, users can first rescale the virtual space to adjust locomotion speed and accuracy and then move accordingly. By combining them, users can traverse the space-scale directly (Furnas and Bederson 1995).

Although multiscale techniques can affect navigation by allowing users to access multiscale spatial information and have multiscale traveling capabilities, it is still unclear exactly what roles multiscale spatial knowledge and multiscale traveling speed and accuracy may play in support of navigation. It is well known that spatial knowledge at different scale levels is critical to navigation (see review in Sect. 2). However, there is little empirical evidence of the use of multiscale traveling in support of navigation,

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although the benefits of multiscale techniques for traveling have been proposed (Furnas and Bederson 1995).

Multiscale traveling is a technique that does not exist in the real world. A better understanding of it will offer new opportunities to not only expand design space in supporting spatial activities in virtual environments, but also deepen our understanding of how people treat space and scale parameters. This paper is an effort to study the use of such interactive scaling in 3D traveling. More specifically, this paper evaluates two multiscale traveling techniques: scaling-then-traveling, a technique allowing users to separate scaling from moving, and scaling-as-traveling, a technique allowing users to combine scaling with moving. The results of this research will help create a better understanding of the ways in which multiscale tools can be more beneficial, and help identify potential cognitive issues associated with the use of multiscale tools in navigation.

The outline of this paper is as follows. The next section reviews related research. Multiscale navigation in virtual environments is discussed in Sect. 3. After a brief description of the design and implementation of two multiscale traveling techniques in Sect. 4, the paper presents an experimental design in Sect. 5 and discusses the results in Sect. 6. The final section concludes the paper by discussing the implications of this study for research and outlines our future research.

2 Related research

People's navigation behaviors in the real world and virtual environments have been studied in various disciplines. Cognitive scientists are interested in spatial cognition of navigators. In geosciences, research focuses are on people's spatial and temporal behaviors and the use of external artifacts (e.g., maps) in wayfinding. In human–computer interaction, research mainly concerns the design of computer-based navigation tools to improve locomotion and the access to spatial knowledge.

Research literature on human navigation behaviors is extensive. Given the specific goal of this research to study multiscale traveling in virtual environments, our review discusses some directly relevant research making up only a small part of all available literature on spatial cognition and navigation support. The focus is on spatial cognition theories and navigation tools derived from them, designs to support navigation in 3D virtual environments, and multiscale user interfaces and multiscale navigation.

2.1 Spatial cognition and navigation support

A widely accepted theory in spatial cognition is that people use cognitive maps to store and structure spatial knowledge. A cognitive map is usually regarded as an internal representation of the spatial structures of an external environment (Golledge 1999; Tolman 1948). Constructing cognitive maps relies on such spatial knowledge as landmark knowledge, route knowledge, and survey knowledge (Hart and Moore 1973; Piaget and Inhelder 1967). These three forms of spatial knowledge are grouped and organized to provide users with a comprehensive understanding of space at different levels of abstraction (Kosslyn et al. 1978). Such structures allow people to access necessary spatial knowledge effectively in solving spatial problems (McNamara et al. 1989; Stevens and Coupe 1978), such as wayfinding (Passini 1984).

In real life, navigation tools usually support human wayfinding activities by mediating activities related to cognitive maps. As an external artifact to assist spatial knowledge acquisition (Bagrow 1985), a map provides various kinds of spatial information that are critical to the constructions of cognitive maps. Examples of such spatial information include names of streets, locations of large spatial structures (e.g., parks, malls, etc.), shapes of prominent buildings, and so on. Also, a map can help people to know where they are and whether they proceeding correctly to their destination. In this situation, the map functions as a cognitive interface that connects a person's internal spatial understanding or a spatial action plan (e.g., a route to destination) with the real environment (Barkowsky and Freksa 1997). Automobile navigation tools, usually equipped with a global positioning system (GPS), can further help to lessen cognitive burdens in navigation by delegating route planning tasks to computers.

Passini (Passini 1984) argued that wayfinding in navigation is a problem-solving task that includes three processes: knowing an environment through cognitive mapping or information gathering, making an action plan to reach a destination, and executing that plan in the environment. Based on this theory, maps and GPS-based navigation systems help to address issues associated with the first two processes. Tools to support the third process, plan execution, are rare. This may be because human beings usually have to be involved in the control of physical movement, either directly (e.g., walking) or indirectly (e.g., driving), in dealing with real-world situations (e.g., road conditions, traffic, and so on) that restrict or confine movement. One exception is autopilot systems on airplanes and ships. Compared with movement on land, traveling by air on sea along pre-defined routes involves fewer unexpected factors and may be automated more easily.

2.2 Navigation in 3D environments

Although the traditional theories of spatial knowledge acquisition and organization have been challenged by scientists (Hirtle and Hudson 1991; Montello 2001; Presson and Montello 1988; Tversky 1993), these theories have significantly influenced research on spatial cognition and navigation activities in 3D virtual environments. It has been found that spatial cognition in virtual environments is similar to that in the real world (Ruddle et al. 1997; Wilson et al. 1997; Witmer and Kline 1998). Many 3D navigation research projects have focused on designs to help people access different kinds of spatial knowledge. One common technique for accessing high-level survey knowledge is to use 2D overview maps, as seen in many computer games. Overviews also can be 3D structures (LaViola et al. 2001; Leigh and Johnson 1996; Stoakley et al. 1995), which tend to be easier to use than 2D maps because of the similarity of 3D structures to the real world (Liben 2001). Design efforts have also been made to help to acquire landmark knowledge (Pierce and Pausch 2004; Vinson 1999). Route knowledge in virtual environments still largely relies on visual information such as key landmarks (Elvins et al. 1997), given that there is less body movement in virtual navigation. In addition to these designs focusing on the presentation of spatial information, design considerations also have been given to improving the organization of spatial structures. In his seminal work, *Image of the City* (Lynch 1960), Lynch argued that a better organized environment is easy to navigate in the real world. Darken and Sibert (Darken and Sibert 1996) extended this principle to virtual environments.

As seen, this school of research almost follows the same trajectory of navigation support in real life. The primary focus of this school is on supporting spatial information acquisition and organization. While access to spatial knowledge is important to navigation (Downs and Stea 1973; Golledge 1999; Thorndyke and Golding 1983), travel control is also critical to navigation in virtual environments (Bowman et al. 1997; Mackinlay et al. 1990).

There is another school of research that focuses on the execution of spatial movement in navigation. Different from the real world, virtual worlds actually allow the system to execute movement and take a user to any virtual place automatically. (This approach is similar to the use of autopilots in the real world.) These two schools are distinguished as wayfinding support, which concerns the acquisition and application of spatial knowledge, and traveling support, which focuses on locomotion control in 3D (Bowman et al. 1997).

Many designs have been proposed to achieve quick movement and accuracy in reach a destination. Example designs include logarithmic movement functions (Mackinlay et al. 1990), system walking (Hanson et al. 1997), and even teleportation. However, most of these techniques do not allow users to control traveling. It has been argued that interactive control over traveling is also valuable to users in virtual environments (Bowman et al. 1997), echoing the similar claims about the importance of interactive activities to people's understanding of the environment in the real world (Evans and Pezdek 1980; Gibson 1979; Leshed et al. 2008; Parush et al. 2007). Some efforts have been made to allow interactive manipulation of locomotion speed and accuracy. Ware and Fleet (Ware and Fleet 1997) presented a design which gives users the control of flying speeds.

It should be noted that despite the distinction between wayfinding support and traveling support, in many situations, it is impossible to totally separate locomotion control from spatial knowledge. While some designs like teleportation do not need visualized spatial information to start and stop navigation, many interactive traveling tools still require users to have certain visual guidance in traveling, at least at the beginning of traveling. The design of the World-in-Miniature (Stoakley et al. 1995), for example, integrates a 3D overview map with teleportation so that a user can specify a target from the overview and then let the system execute the view movement. The speed-coupled flying tool (Tan et al. 2001) associated the height and tilt of the viewpoint with flying speed, gives users different kinds of spatial knowledge at different locomotion speeds.

While designs to support information gathering and movement execution are often seen in virtual environments, it is rare to find research to support route planning, the second process in Passini's model. This may be because many factors that restrict physical movement in the real world no longer exist in virtual environments so there is no need to follow particular routes. For example, in virtual environments, a user can move "through" buildings and take a more efficient path than by following virtual streets.

2.3 Multiscale navigation

The multiscale user interface (Bederson and Hollan 1994; Perlin and Fox 1993) technology allows users to change their interaction scales. In multiscale user interfaces, users can zoom into and out of their workspace to control the content and context information presented on the screen and can change their interaction domains. Figure 1 shows three screen shots from a multiscale user interface, Pad++ (Bederson and Hollan 1994). The successive views, from Fig. 1a–c, illustrate a zooming-in operation. Reversing the order, views, from Fig. 1c–a, exemplify a zooming-out operation. As seen, zooming into and out of the workspace changes the rendered size of objects. At the same time, zooming also affects a user's action domain. When the user zooms in from Fig. 1a to c, the visible area of the workspace is decreased, but the users can work on more details. Zooming out from Fig. 1c–a, the user can reach larger workspace.

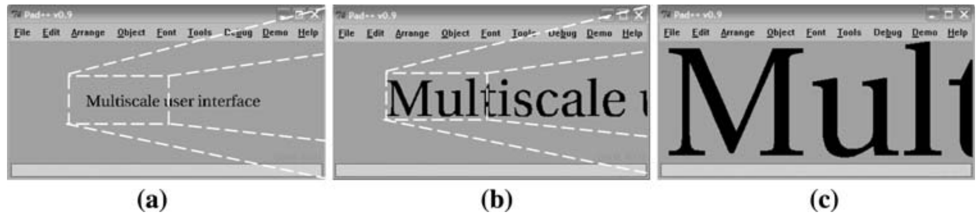

Fig. 1 A 2D multiscale user interface that shows three successive views at different scales. Perspective lines added to this figure to show the origin of each successive view

Navigation in 2D multiscale user interfaces has been studied. Some research found that multiscale interfaces can aid navigation by providing richer context and content information (Páez et al. 1996; Schaffer et al. 1996) and by better supporting navigation processes (Combs and Bederson 1999). On the other hand, it also has been reported that multiscale interfaces may cause problems in navigation because zooming operations can increase the information complexity with which our human visual working memory has to deal (Plumlee and Ware 2006). One explanation for the conflicting results on multiscale navigation may be due to the different tasks used in these projects (Ghosh and Shneiderman 1999; Hornbæk et al. 2002), making it difficult to compare results. This stream of research largely focused on the presentation of visual information that is critical to finding navigation destinations.

The research on multiscale traveling is not often seen, although its potential was suggested long ago (Furnas and Bederson 1995). One exception is the Critical Zones project (Jul and Furnas 1998), which presented some traveling-related issues that may lead to disorientation in multiscale user interfaces. Some research studied the use of pointing devices in view control in multiscale navigation (Guiard et al. 1999), but user tasks studied in these projects were more about generic multiscale pointing skills, such as the accuracy of object pointing, than about locomotion or traveling control. Although in 2D multiscale user interfaces, view panning (a workspace travel technique) is usually controlled by dragging pointing devices, what is important to traveling control is the movement direction and distance of pointing devices, not the accuracy of object pointing.

Multiscale user interfaces allow users to change the presentation of spatial structures and their action domains. Such features offer some benefits to 3D navigation. Multiscale tools can help users better access spatial information through multiscale views. The scaled-down models seen in (LaViola et al. 2001; Leigh and Johnson 1996; Stoakley et al. 1995) are good examples of the use of multiscale views, although compared with 2D multiscale designs, these 3D models still face challenges in building miniatures that show differently sized areas with different levels of detail across a larger scale range and support fully interactive control over scaling (Durlach et al. 2000). Recently, some multiscale tools have been designed to support 3D navigation. Kopper et al. (2006) presented a tool to help users maintain spatial orientation in cross-scale navigation. Their focus on the access of spatial information is different from that of this paper. The Seven-League-Boots technique (Interrante et al. 2007) can increase locomotion speed in the intended direction of travel. However, this tool only provides users with a choice of two speeds.

In summary, most navigation research reviewed above can be divided into two schools: one school focuses on supporting the access and organization of visual information that is important to movement, and another school which focuses on supporting actual movement. The research presented in this paper belongs to the second school.

3 Traveling in multiscale virtual environments

Integrating multiscale techniques into virtual environments can potentially improve both wayfinding and traveling. How multiscale locomotion speeds may affect spatial knowledge in 3D has been studied by some researchers (Interrante et al. 2007; Williams et al. 2006). Our other paper investigates the relationship between cross-scale locomotion speed and cross-scale spatial information (Zhang 2008). In this paper, we are interested in the benefits and costs of different multiscale traveling mechanisms and in understanding their efficacy and effectiveness in traveling in large virtual space.

Although the impact of scaling on spatial knowledge in traveling is not our focus, as mentioned previously, it is often difficult to totally remove the impact of spatial knowledge on traveling as long as visual information is provided. In this research, we minimize the impact by simplifying the virtual scenes used in our experiment so that the change of spatial information in scaling could be as minimized. The design of the virtual scene will be described in Sect. 5. In this section, we describe the basic ideas of multiscale traveling and present their features.

3.1 Avatar metaphor

An avatar is a representation of a user in a virtual environment. It usually appears as a virtual human. In many virtual environments, in particular collaborative virtual environments, an avatar's body parts are often used to define a user's interaction parameters (e.g., virtual eyes to represent viewpoints, virtual arms to indicate manipulation distance, and virtual legs to suggest movement speed).

Avatars play a very important role in virtual environments. In collaborative environments, they provide awareness information to support collaboration (Benford et al. 1994; Zhang and Furnas 2002). In our research, we chose the avatar metaphor for its conceptual significance in understanding the association of different interaction parameters. In the real world, our human body is an entity that ties and conveys our sensory organs. In virtual environments, it is not necessary to always require associating these size-related interaction parameters with the physical properties of the avatar's body parts in general 3D environments. Some scaling tools for manipulation do not use an avatar metaphor at all (Mine et al. 1997; Pierce and Pausch 2004). Our research emphasizes how locomotion speeds change as a result of different spatial relationships between users and space. The avatar metaphor can easily model such relationships. Under the avatar metaphor, users can make giants of their avatars, enabling them to go faster and reach farther, or become ants, which move slowly but more accurately. By manipulating the size of their avatars relative to the space, users can control their locomotion speed and accuracy. In our usability study, which will be presented later, this metaphor was used to help subjects understand multiscale traveling.

The avatar metaphor also can help to understand how spatial perception, such as depth perception and size perception, can be affected by scaling. People rely on various kinds of visual cues to estimate distance and object size (Kaufman 1974). Most often seen cues include static pictorial cues like the relative sizes of objects, occlusion, elevation, binocular disparity, and so on. People also use kinetic cues from the viewpoint movement in distance estimation by comparing the difference between images before and after the movement. Multiscale techniques could alter some of these visual cues and consequently, affect spatial perception. For example, scaling can change the view elevation, so occlusion patterns vary from scale to scale. Or, when stereo views are available, scaling will affect the relative position of left and right viewpoints, which determines binocular disparity that human beings are good at using to compute depth. Scaling also can affect kinetic cues. With different speeds at different scales, users may have different motion parallax and not only understand the space differently, but feel differently about it as well.

3.2 Scaling-then-traveling

The scaling-then-traveling technique implies two separate activities: choosing a desirable interaction scale, and traveling with corresponding speed and accuracy. Under the avatar metaphor, changing a user's interaction scale enlarges or shrinks the size of the user's avatar relative to the virtual space. This changes the value of interaction parameters relative to the virtual space. Interacting with small things like atoms, the user can shrink the avatar down (or equivalently magnify the world) to see lattice configurations and move accurately. Working on large things like planets in a planetary system, the user has to magnify the avatar (or equivalently shrink the world) to obtain the big picture of the planetary system and move quickly.

These two scaling metaphors, scaling as resizing the user's avatar and scaling as resizing the world, are equivalent mathematically, but they imply different ways to execute scaling operations. In particular, these two metaphors rely on different scaling centers.

3.3 Scaling center

Any scaling operation has a "fixed point," a point that remains constant, and around which everything else either expands (moving away) or contracts (moving closer). This fixed point is called the "scaling center." Mathematically, the scaling center can be any point in the 3D world.

In a virtual world with a ground plane on which a user walks, scaling the size of an avatar makes the standing point of the avatar the scaling center. This choice produces the effect of the avatar growing bigger or smaller as they stand still in the world. This scaling metaphor suits the scaling-then-traveling technique quite well, because scaling here alters only a user's interaction capabilities (e.g., speed), not the user's position.

On the other hand, seeing scaling as resizing the world actually allows any point in the world to become the scaling center. The whole world is resized around arbitrary scaling centers. While the avatar's position remains constant in the underlying space, objects in the world shrink toward, or expand away from, the scaling center. As a result, the avatar is effectively moved through the world as it is resized around these arbitrary centers.

3.4 Scaling-as-traveling

Because scaling with different scaling centers could possibly move a user from one place to another, a user can use scaling as a way to travel around. While the scaling-then-traveling technique clearly separates scaling and traveling, this scaling-as-traveling technique integrates scaling and traveling and allows users to take optimized navigation paths by traversing the space and scale simultaneously (Furnas and Bederson 1995). Some 2D multiscale environments like Pad++ (Bederson and Hollan 1994) have implemented this tool, allowing users to combine zooming and panning in navigation.

Figure 2 shows a 3D scenario where a user needs to travel to a distant target by primarily using scaling tools. Figure 2a indicates the initial position of the user, the target A, and the travel distance d. Using scaling tools, the user can first choose a scaling center C to gradually scale down the world, making the target smaller and bring it closer, as seen in Fig. 2b. Then, after moving the scaling center to C' close to the target (Fig. 2c), the user can rescale the world around C' gradually and eventually reposition it near the target (Fig. 2d). If the distance between the initial and target position is very far, this scaling method might be potentially faster, compared with simply moving it.

This scaling-as-traveling technique would provide users with a navigation method which does not exist in the real world. In virtual environments, some interaction designs do not follow our real-world practice. Rather, they leverage those unique features only available in virtual environments to help users achieve their goals in innovative ways. A good example of such designs is using teleportation for traveling. While the scaling-as-traveling technique also is a design without a real-world parallel, it may have the potential to greatly improve user performance in a virtual world.

Using scaling to support navigation could have both advantages and disadvantages for navigation. On one hand, these two tools may provide more efficient ways to navigate due to changeable action domains and shorter navigation paths. On the other hand, changing interaction scale and manipulating a scaling center demands time. To understand how these two multiscale tools may help or impede 3D navigation, we implemented a multiscale virtual environment and conducted a controlled experiment to compare them with conventional navigation techniques.

4 Design and implementation of two scaling tools

The design and implementation of these two scaling tools are simple. In this section, we describe some technical details related to the design and implementation. We also compare these two multiscale traveling tools with other similar tools.

4.1 Scaling control and modeling

In our design, scaling is made one of the most important operations in user interaction. The interaction scale is treated as a basic and first-class spatial parameter like

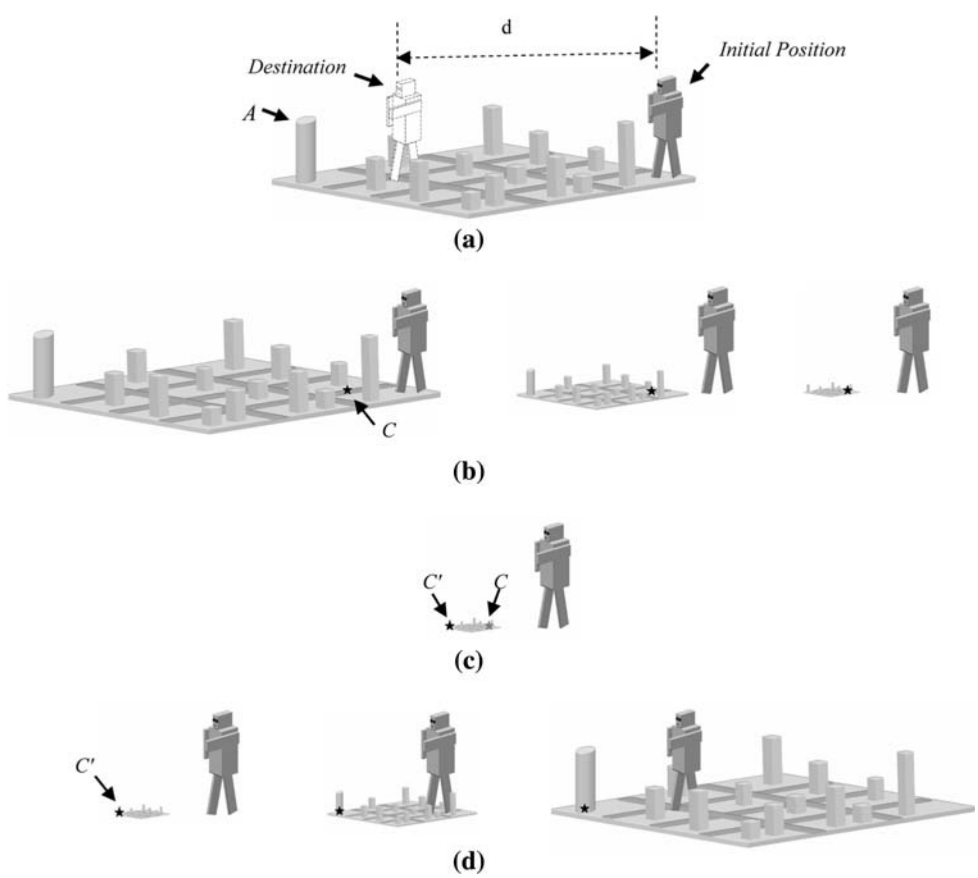

Fig. 2 Scaling-as-traveling. **a** A user's initial position, the target A, the travel destination, and the travel distance d. **b** The user contracts the world around a scaling center C. **c** The user adjusts the position of the scaling center to a new position C'. **d** The world is expanded around the new scaling center, and the user moves closer to the target A

observation location and observation orientation, rather than as a supplemental factor. Users can directly control interaction scale, through a keyboard or mouse. They can be a giant one moment to enjoy a big view of spatial structures and a great action domain, and be a small ant at another moment to leverage the detailed view and precise action.

The scale value is modeled as a logarithmic function by following the designs in other multiscale user interfaces, such as Pad++ (Bederson and Hollan 1994). This logarithmic approach makes the change rate of the scale value a constant, which in turn leads to a constant change rate of views in scaling. Such a design allows users to easily control scaling operations and obtain necessary information at different scale levels. With other functions, such as linear, users may face problems in scaling control when the scale value is very large or small.

4.2 Design of scaling-then-traveling and scaling-as-traveling

The design of the scaling-then-traveling tool is simple. It only involves modeling the size of a user's avatar and locomotion speed at different scales. In this research, these two parameters were made proportional to the value of interaction scale.

The design of the scaling-as-traveling technique also is straightforward, except for the positioning of the scaling center. Unlike in 2D multiscale user interfaces where users can point the cursor to any visible point on a workspace to position the scaling center, in 3D, the screen position of the cursor cannot be used to define the scaling center because the screen position represents an infinite 1D locus of points. Users have to specify the depth of the scaling center. Using 2D pointing devices to specify the spatial position of scaling center in 3D is not ideal (Bier 1986; Nielson and Olsen 1986). Directly manipulating a 3D position is difficult. Even in immersive virtual environments, where body gestures can be involved in directly manipulating near objects, controlling objects beyond the arm-reach range is still problematic (Mine 1995).

To address this 3D positioning issue, we adopted a two-step approach to specify the position of a scaling center: (1) determine its screen projection position by allowing users to drag and drop the point directly; (2) adjust the depth of the scaling center relative to the user's viewpoint, while keeping its screen projection position fixed. Figure 3 shows a control procedure under this design. In Fig. 3a, the scaling center is rendered as a cross. The cross can be dragged and dropped to any desired screen position to establish a scaling center, as shown in Fig. 3b. Then, users can change the depth of the scaling center while keeping its screen position fixed (Fig. 3c). When the user moves, the scaling center also moves with the user, but its position in the user's view does not change.

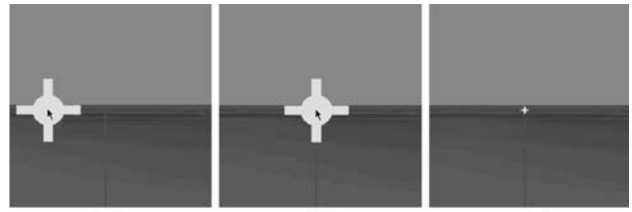

Fig. 3 Control of the scaling center: **a** the initial position of the center represented by the *cross*; **b** the center after being dragged and dropped; **c** the center after depth adjustment

4.3 Implementation

Our implementation is based on a scene-graph model in Java 3D (Fig. 4). Under the root node, there are two branches: a view branch for the avatar and the scaling center object, and an object branch for all other objects. Each branch has a transformation node on the top.

The scaling-then-traveling tool only involves changing the scale value of the top transformation node of the view branch, $\boldsymbol{T_v}$. Its algorithm is as follows:

```
while (scaling) {
  if (scaling_up_the_world)
        reduce the scale factor of Tv by a factor of α;
  else
        increase the scale value of Tv by a factor of α;
}
```

The scaling-as-traveling tool requires changing the translation and scale values of the top transformation node of the object branch, $\boldsymbol{T_o}$. The algorithm is:

```
get the position of the scaling center in the local coordinates of view branch, Pl;
while (scaling) {
  get the transformation of the viewpoint in the global coordinates, Tv;
  get the position of the scaling center in the global coordinates, Pw, = Tv · Pl;
  translate To by -Pw;
  if (scaling_up_the_world)
        reduce the scale value of To by a factor of α;
  else
        increase the scale value of To by a factor of α;
  translate To by Pw .
}
```

In both algorithms, the factor of α is a fixed parameter that determines the rate of scaling. Its value should be small to produce continuous and smooth visual results in scaling. In systems like Pad++ (Bederson and Hollan 1994), it is set as 5%.

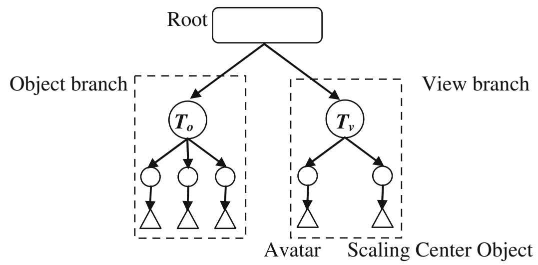

Fig. 4 Scene graph in the implementation. *Circles* represent transformation nodes. *Triangles* symbolize geometric objects

4.4 Comparison with other multiscale navigation tools

Integrating scaling operations into virtual environments is certainly not new (Mapes and Moshell 1995; Robinett and Holloway 1992). Many research projects (Leigh and Johnson 1996; Mine et al. 1997; Stoakley et al. 1995; Ware and Fleet 1997) have allowed users to see and interact with virtual environments at different scales, but these designs usually do not allow users to control scaling operations directly and interactively. Also, these designs, usually do not address interactive traveling issues directly. And, system-driven locomotion tools (Hanson et al. 1997; Mackinlay et al. 1990; Tan et al. 2001) do not support interactive control during traveling. Although users can specify the travel destination, the system deprives users of locomotion control. These approaches may help to reduce potential cognitive burdens associated with the adjustment of locomotion parameters (e.g., speed, direction, and accuracy), but they also may prevent users from benefiting from dynamical and active exploration.

Both scaling-then-traveling and scaling-as-traveling techniques have been implemented in 2D user interfaces. In the 3D domain, some designs follow the scaling-then-traveling metaphor. For example, the Seven League Boots (Interrante et al. 2007) allows users to switch between two pre-defined speeds. However, it does not provide users with the flexibility to pick other locomotion speeds, while our design does. Designs to support scaling-as-traveling are rarely seen in 3D.

5 Experiment

Based on a desktop multiscale environment implemented with Java 3D, an experiment was conducted to study the effectiveness of these two multiscale traveling tools. The hypothesis of this experiment was that these two multiscale traveling tools could facilitate traveling, particularly long-distance traveling, because the time spent on scaling-related activities can be better justified by the time saved in actual traveling. Also, given that the scaling-as-traveling allows direct traversing of both space and scale, this tool may improve traveling performances even more.

5.1 Subjects

Recruited by e-mail, 12 paid student subjects, ages 18–30, participated in the experiment. They all reported to have 3D virtual environment experience with either PCs or game consoles.

5.2 Apparatus

A Dell PC (1.8 GHz P4 CPU, 216 M memory, a GeForce2 GTS graphics card, and a 15-in. monitor) was used in the test. The screen resolution was $1{,}024 \times 768$ with an 800×600 view of the virtual environment.

User interactions were through keyboard and mouse. Subjects could use four arrow keys in moving to four different directions—forward, backward, left, and right. Each keystroke was mapped to a default movement displacement in virtual space. When the interaction scale was changed, the displacement of each keystroke was the product of the default displacement and the interaction scale. Subjects could also rotate their view orientations by the Ctrl key and left/right arrow keys. The view rotation step associated with each key stroke was fixed and did not change with scale. No view tilting was allowed. To control the depth of the scaling center, subjects could increase or decrease the viewing distance by simultaneously pressing the Alt key and moving the mouse up or down, respectively.

Scaling was controlled by the combination of mouse-button pressing and mouse movement. Pressing the left mouse button and moving the mouse up scaled down the world. Pressing the button and moving the mouse down scaled up the world. The change rate of the scale value in our logarithmic algorithm was 5% per step. The time frequency was set in such a way that the scaling transformation was animated with a frame rate of about 30 frames per second. Because the change rate of the scale value was a fixed parameter, only the mouse movement direction was relevant to the scaling transformation. The speed of mouse movement did not affect scaling.

The scale value was presented on the screen in a numerical format. Subjects could read the number and know at what scale level they were working. A maximum level of the scale value was set to prevent subjects from getting lost. In multiscale environments, users could be disoriented when they reach a very large interaction scale and get no visible spatial information to guide navigation (Jul and Furnas 1998). Because we were interested in traveling, not wayfinding, setting a ceiling scale value could help to reduce possible noises, if there is any.

5.3 Procedure

The experiment was a 3×2 within-subject design by crossing navigation tools and navigation distances. The three different navigation tools were scaling-then-traveling (SCALING-THEN-TRAVELING), scaling-as-traveling (SCALING-AS-TRAVELING), as well as a regular virtual environment (NO-SCALING), which only allowed subjects to move around and established the baseline condition for comparison. Two navigation distances were 20 m (CLOSE) and 100 m (FAR).

Each subject was first briefed on the features of multiscale environments. In additional to a written description, a short video introduction to the multiscale environment also was provided. The video introduction was about 50 s long, and presented scenes in two windows: the window where a subject's primary activities happened, and the window where the subject's avatar was observed from a third-person view. Figure 5 shows two snapshots from the video before and after scale change.

The test scene was simple. In each treatment, there were only two objects in virtual space: a ground plane with a size of 2×2 km, on which subjects would travel, and a 50-m high target pole on the ground. This scene was made simple on purpose by minimizing the impact of spatial knowledge on traveling.

In each test, subjects were initially positioned in the center of the ground plane, and a visible target pole was placed at one of two possible distances. A default scale value was 1.0, and the default height of an avatar is 1.8 m with an eye level of 1.68 m. The default displacement of each key stroke in moving control was 0.3 m. Holding a key allowed subjects to move 1.2 m/s. The ceiling scale value was set to be 30.0 so that even a subject would reach the upper scale limit with a view at the level of about 51 m; the subject could still see the target pole in the view.

Subjects were required to travel to the target, as close and as fast as possible. To achieve this goal, they must place themselves in such a position that any further movement toward the target pole would make the target pole disappear. In 3D graphics a viewing frustum typically clips away objects when a user's viewpoint gets too close. The closest possible position of a visible object in a 3D world is on the near plane of a view frustum, with the closest possible distance D (Fig. 6).

Subjects were required to accurately position themselves, in terms of the distance to a target. When a subject thought a task was finished, the subject needed to click a button to initiate a procedure to check whether the viewing distance to the target was within the range of [D, $D + error$]. If not, the subject was informed that the task had not been finished. The error range used in our test was 0.50 m. In two treatments with scaling tools, subjects could choose any interaction scale during the test, but they must end the task at the default scale, 1.0, within a 5% error range. Such a task required both traveling speed and accurate final location.

Under each treatment, subjects were given 5 min to practice moving around, scaling, and controlling the scaling center. Then, they did the task twice. When a task was finished, subjects were given a score based on the viewing distance to the target and the time spent. The closer the view distance to a target pole was, the higher the score. The

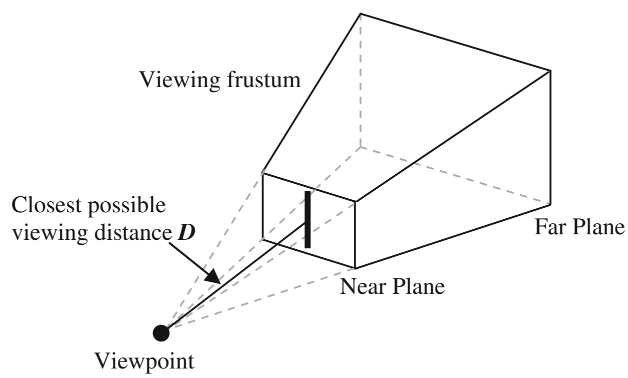

Fig. 6 Viewing frustum and the closest possible viewing distance of a visible object

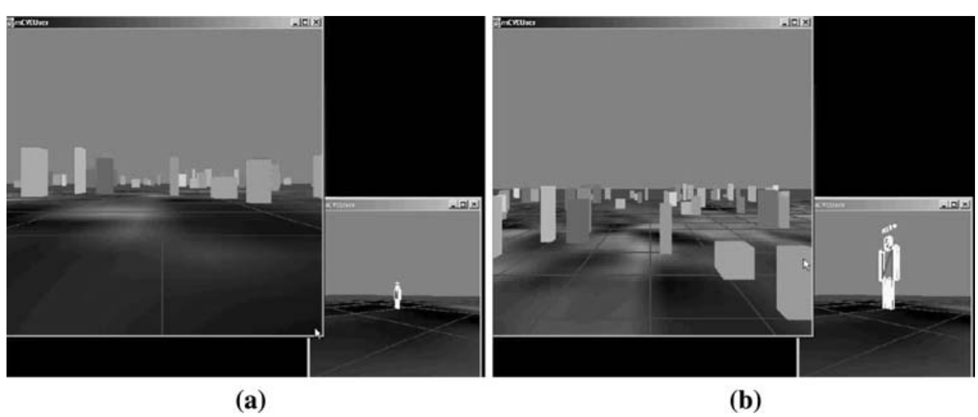

Fig. 5 Scene shots of the video introduction to multiscale virtual environments. **a** the primary view (*upper left*) and a third-person view (*lower right*), before scale change; **b** the two views after scale change

faster a task was finished, the higher the score. This score was only an incentive to encourage subjects to stay as close to a target pole as possible and finish the task in as little time as possible. To avoid the carry-over effect of different navigation tools, NO-SCALING, SCALING-THEN-TRAVELING, and SCALING-AS-TRAVELING tools were counter-balanced.

Data collection focused on task-completion time and subjects' keyboard and mouse behaviors. In this experiment, all subjects finished all tasks successfully. Thus, in this error-free experiment, task-completion time became critical. Keyboard and mouse events also interested us because they provided detailed information about what subjects did. These events were recorded with a sampling frequency of 1-s. After a test, subjects were given a post-test survey to assess their perception of the usefulness of two scaling tools.

6 Results

6.1 Task-completion time

Figure 7 shows the experiment results. As expected, using multiscale tools for short-distance locomotion was more costly. For the long-distance travel, while the scaling-then-traveling tool led to a shorter travel time than the baseline treatment ($t_{11} = 1.871$, $P < 0.045$), the hypothesized potential of the scaling-as-traveling tool was not found.

By further comparing subject performances in the SCALING-THEN-TRAVELING and NO-SCALING treatments with an ANOVA, we found that the interaction between target distances and treatments to be marginally significant ($F_{1,47} = 3.27$, $P = 0.077$).

6.2 Activity logs in scaling-as-traveling

Five different activities could be found by analyzing activity logs: moving, rotating, scaling, adjusting the scaling center, and pausing. Figure 8 shows activity logs of two subjects in traveling to the FAR target. Figure 8a is the log of the subject who finished the task with the shortest time. The horizontal axis is time in seconds. The vertical axis lists five actions. The dots and lines tell what a particular activity happened and for how long. The log of the subject who finished with the longest time is seen in Fig. 8b.

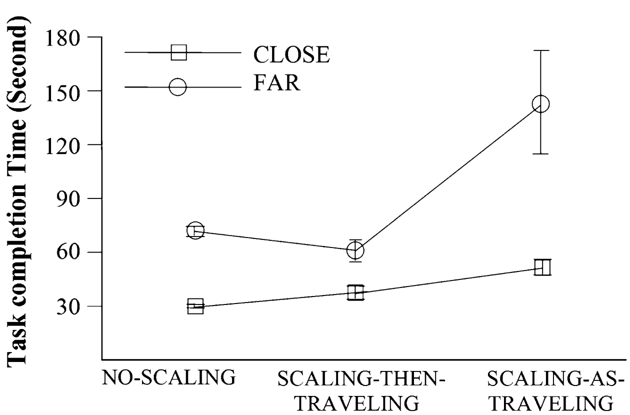

Fig. 7 Time comparison: two distances in three treatments

7 Discussion

Results indicate that the scaling-then-traveling technique offers some benefits to long-distance traveling, but the scaling-as-traveling technique seems counter productive. In this section, we discuss what may contribute to such results, as well as the opportunities and challenges of these two multiscale traveling tools.

7.1 Benefits of multiscale control of action domains

The scaling-then-traveling technique seems very promising. To subjects, it was more like a regular navigation tool enhanced with changeable locomotion speed and accuracy. In addition to results seen in Fig. 7, all subjects reported in their post-test questionnaires that it is easier to understand and use this tool. We believe that further increasing travel distance will make the interaction between traveling

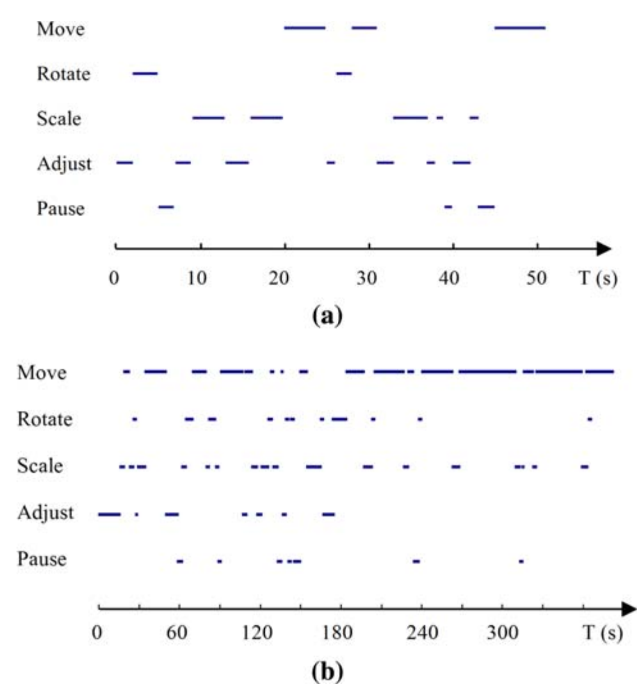

Fig. 8 Activity logs of two subjects. *Dots* and *lines* indicate the time and the length of an activity: **a** the log of the fastest subject; **b** the log of the slowest subject

distance and NO-SCALING versus SCALING-THEN-TRAVELING treatments more significant, because using the scaling tool to obtain proper movement speed and accuracy becomes more efficient, even considering the time required by scaling operations.

What distinguishes the scaling-then-moving technique from other locomotion designs, such as the logarithmic functions (Mackinlay et al. 1990) and the Seven League Boots (Interrante et al. 2007), is users' direct and interactive control over movement. Users can decide their locomotion speed and accuracy at any time, and do not have to follow a particular navigation trajectory or speed predetermined by the system. Such a control of action domain could be valuable for exploration-oriented navigation, in which users know roughly where to go, but do not know the coordinates of a particular destination. This technique allows users to adjust their movement in real time.

Certainly, more interactive control requires more user involvement. Then, more challenges may rise when users have to understand their current positions, make decision on future movement, and execute action plans. In an unfamiliar environment, users may find that doing these tasks may lead to more mistakes and slow down navigation. This might be one of the reasons for the unexpected results under the scaling-as-traveling technique.

7.2 Challenges in using scaling-as-traveling

It was predictable that the benefits of the scaling-as-traveling tool would not be significant for short-distance traveling, but it was a surprise to see it failed to improve long-distance traveling by a large margin. This failure may be related to some challenges in executing this scaling tool and in understanding virtual scenes in scaling.

7.2.1 Difficulty in executing scaling-as-traveling

The post-test surveys showed that all subjects but one rejected the scaling-as-traveling technique by saying it was too difficult to use, although they all agreed that its principle was very understandable. The activity logs of subjects can help us further understand what problems they may have had.

Figure 9 shows the activity transition diagrams of two subjects based on Fig. 8. Figure 9a is the diagram of the subject who completed the task with the shortest time, and Fig. 9b is that of the subject with the longest time. Each activity is represented as a circle with a size proportional to the percentage of time spent on it. The arrows show transition direction between two activities, and the thickness of each arrow corresponds to the frequency of a transition.

Clearly, these two diagrams have different patterns, which may imply what may affect the use of the scaling-as-traveling tool. The fastest subject relied primarily on directly adjusting the scaling center in the test. While this subject spent 30% of the total time on this activity, the slowest subject allocated only 10% of the total time to the same activity, but 60% to movement. Another difference is the transition frequency between the moving activity and the scaling activity. While a very low transition frequency could be observed from the fastest subject's action, the slowest subject changed far more frequently between moving and scaling than any other pairs of activities. Similar patterns also can be found with other subjects who finished the tasks slowly.

These differences may imply some challenges those slow subjects had when using scaling-as-traveling tools. One of the challenges may be a difficulty in setting up the scaling center directly. Instead of manipulating the depth of scaling centers directly as did the fastest subject (Fig. 10a), the slowest subject may have chosen an easier way to adjust the scaling center indirectly by walking (Fig. 10b). As seen, the transition between moving and scaling is more frequent in Fig. 9b than in Fig. 9a. This phenomenon may indicate the use of the indirect approach in positioning the scaling center, which compared with the direct manipulation of the scaling center location, was less efficient, though easier to use.

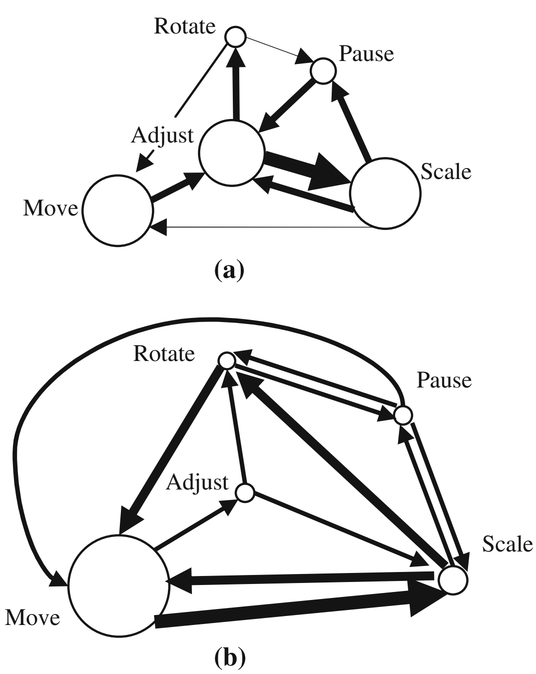

Fig. 9 Action transition diagrams. *Circles* represent activities with a size proportional to the percentage of time spent. *Arrows* indicate the direction and frequency of action transition: **a** the fastest subject; **b** the slowest subject

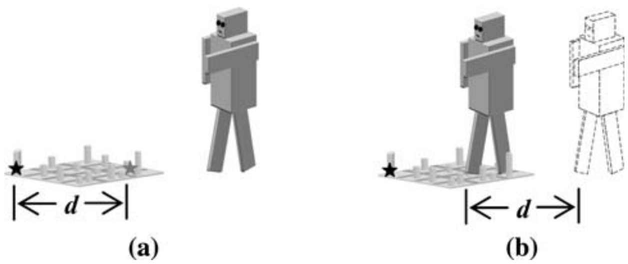

Fig. 10 Two different ways to adjust the position of a scaling center. **a** Directly moving the center by a distance *d*. **b** Indirectly moving the center by walking a distance *d*

7.2.2 *Difficulty in understanding space*

Another challenge might be related to the understanding of the coupling of scale and space. With the scaling-then-traveling tool, users can execute scaling operations first and then moving in space. Thus, a user can think about scale and space separately. The scaling-as-traveling tool, however, ties scale and space together. This coupling may require skills to specify a scaling center appropriate to the travel goal and foresee what virtual scenes would look like during and after scaling. Without such skills, a user may have to a significant amount of time on fine-tuning their final locations and scales by moving around, scaling up and down, and switching between scaling and moving.

In the post-test surveys, subjects also reported that scaling up and down according to different scaling centers often led to very confusing scenes. This feedback may suggest some challenges subjects faced in understanding the space-scale.

The first challenge could be related to understanding the changes of the virtual scene when it was scaled according to an arbitrary point. The scaling-as-traveling technique does not simulate any real-world experience people have had. The NO-SCALING treatment provided subjects with view transformations very similar to their everyday life. The changeable locomotion speed and accuracy and viewpoint offered by the SCALING-THEN-TRAVELING treatment can be experienced in different kinds of real-world transportation modes. Compared to them, in the SCALING-AS-TRAVELING treatment, virtual scenes were transformed in a way that subjects had never experienced in the real world. Interpreting such unfamiliar views could be difficult.

Furthermore, subjects also may have had a challenge in correctly perceiving the distance of the scaling center. This misperception could slow down the task, because subjects may have to readjust the scaling center if they determined the depth of the scaling center was not what they had expected. Depth perception in virtual environments still relies on various pictorial cues people use in the real life (Witmer et al. 1996), such as relative sizes of objects, occlusion, elevation, texture gradients, linear perspective, familiarity, and so on. In our experiment, the virtual space was almost empty for the purpose of reducing the impact of spatial information on traveling, given our primary focus on multiscale traveling control. However, the emptiness of space may have had negative impact on the perception of the position of the scaling center and consequent scaling operations.

7.3 Scaling-as-traveling in 3D and 2D multiscale environments

These two difficulties raise a question: do they only exist in 3D multiscale environment or are they shared by both 3D and 2D multiscale environments? As discussed in Sect. 2, most research on 2D multiscale navigation focused on the acquisition of multiscale visual information. It is rare to see research on leveraging scaling to support interactive traveling. Thus, it is difficult to find empirical results to be compared directly with ours. This section offers our answers to the question.

The difficulty in the manipulation of the scaling center might be unique to 3D environments. In 2D multiscale user interfaces, the scaling center is on a planar surface and can be easily specified. In systems like Pad++ (Bederson and Hollan 1994), a user can dynamically change the scaling center during zooming by moving the cursor around. Such direct manipulation is not feasible in 3D multiscale environments. Positioning a point in 3D space through a 2D point device is a classic problem in 3D user interface design (Bier 1986; Nielson and Olsen 1986). Unless we have a solution to this problem, the manipulation of the scaling center in 3D space will still be an issue.

The difficulty in understanding scale space might be a problem in both 2D and 3D multiscale interfaces. The scaling-as-traveling technique requires users to couple scale with space, and predict object behaviors across different scales. Although there are some empirical results about how spatial objects at different scale levels are organized (Presson et al. 1989; Rieser et al. 1995; Roskos-Ewoldsen et al. 1998) and how spatial cognition may differ between large and small spaces (Bell 2002), it is still unclear how the integration of spatial objects across different scales is done internally. Plumlee and Ware (Plumlee and Ware 2006) pointed out that zooming may actually increase the burdens of visual working memory. This result may imply the difficulty in comparing and integrating spatial information obtained at different scales. Further research is needed in both 2D and 3D multiscale user interfaces to study how spatial information and scale measures are processed by users, what factors may impede the coupling of space and scale, and what tools can be provided to facilitate the coupling.

Recent research on spatial memory in dynamic scenes (Huff et al. 2007; Rump and McNamara 2007) offers some perspective on how people recognize dynamic spatial objects in scaling. For example, it has been suggested that different references systems (e.g., environmental vs. egocentric) (Rump and McNamara 2007) and different mental representations (e.g., dynamic-event vs. film-form) (Huff et al. 2007) are involved in recognizing dynamic objects. These factors also may play a role in multiscale environments. Understanding how they may affect cross-scale object recognition may help to understand the relationship between scale and space in both 2D and 3D.

8 Conclusion

The ability to navigate in large virtual environments is increasingly important. This paper studied multiscale traveling tools. The results provide some insights into 3D navigation designs. First, allowing users to interactively control locomotion speed and accuracy can improve navigation efficiency. Integrating this tool into virtual environments, especially those with a focus on exploration-oriented tasks, can offer users some benefits. The implementation of this tool is fairly easy under current 3D modeling technologies.

Second, despite its theoretical power, the scaling-as-traveling method in 3D navigation was found to be difficult to use due to some challenges in understanding the scene transitions in scaling and controlling the scaling center. However, some subjects still expressed their optimistic views on this tool, even through they found it difficult to use.

While crossing the boundary between space and scale has some potential to support 3D navigation, users need help to cognitively deal with those foreign and confusing space-scale phenomena. To harness the full potential of multiscale traveling tools, more research efforts are needed. We want to focus our future research efforts on the ways people process cross-scale spatial information and use it in guiding spatial activities. A good understanding of this issue will not only extend theories on spatial cognition, but also help to improve the design of multiscale traveling tools in virtual environments.

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