Supporting Learning through Spatial Information Presentations in Virtual Environments

Eric D. Ragan

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Computer Science and Applications

Douglas A. Bowman, Chair
Richard R. Mayer
Christopher L. North
Francis Quek
Tonya L. Smith-Jackson

April 22, 2013
Blacksburg, VA

Keywords: virtual reality, visualization, large-display systems, educational software, spatial information presentations, learning, memory

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Abstract

Though many researchers have suggested that 3D virtual environments (VEs) could provide advantages for conceptual learning, few studies have attempted to evaluate the validity of this claim. A wide variety of educational VEs have been developed, but little empirical evidence exists to help researchers and educators determine the effectiveness of these applications. Additional evidence is needed in order to decide whether VEs should be used to aid conceptual learning. Furthermore, if there is evidence that VEs can support learning, developers and researchers will still need to understand how to design effective educational applications. While many educational VEs share the challenge of providing learners with information within 3D spaces, few researchers have investigated what approaches are used to help learn new information from 3D spatial representations. It is not understood how well learners can take advantage of 3D layouts to help understand information. Additionally, although complex arrangements of information within 3D space can potentially allow for large amounts of information to be presented within a VE, accessing this information can become more difficult due to the increased navigational challenges.

Complicating these issues are details regarding display types and interaction devices used for educational applications. Compared to desktop displays, more immersive VE systems often provide display features (e.g., stereoscopy, increased field of view) that support improved perception and understanding of spatial information. Additionally, immersive VE often allow more familiar, natural interaction methods (e.g., physical walking or rotation of the head and body) to control viewing within the virtual space. It is unknown how these features interact with the types of spatial information presentations to affect learning.

The research presented in this dissertation investigates these issues in order to further the knowledge of how to design VEs to support learning. The research includes six studies (five empirical experiments and one case study) designed to investigate how spatial information presentations affect learning effectiveness and learner strategies. This investigation includes consideration for the complexity of spatial information layouts, the features of display systems that could affect the effectiveness of spatial strategies, and the degree of navigational control for accessing information. Based on the results of these studies, we created a set of design guidelines for developing VEs for learning-related activities. By considering factors of virtual information presentation, as well as those based on the display-systems, our guidelines support design decisions for both the software and hardware required for creating effective educational VEs.

Acknowledgements

I am grateful for the help and support of so many people along my way to through the PhD program. Unfortunately, mentioning all of these people would probably double the length of this document, but I will try to at least express my gratitude for a few specific individuals.

I would like to especially thank Dr. Doug Bowman for being a better advisor than I could have asked for. His advice and guidance helped me to grow as a researcher. Without his super-human levels of responsiveness and organization, this work could have taken twice as long. He provided encouragement through the rough stretches and caution during the overly-ambitious periods. Most importantly, he had the patience to put up with me.

I would also like to thank the members of my advisory committee, Dr. Richard Mayer, Dr. Chris North, Dr. Francis Quek, and Dr. Tonya Smith-Jackson, for all of their feedback, suggestions, and helpful discussions about my dissertation work and research in general. I must also extend a special thanks to Dr. David Hicks for our brainstorming sessions and his expertise in history education. Further, I thank Dr. Kathryn Logan for her support and help getting me involved with the National Institute of Aerospace, and Paul Brewster and Jeff Antol at NASA Langley Research Center.

I also want to thank all the students and professors that I have had the fortune of working with at the Center for Human-Computer Interaction. Dr. Yong Cao, Ajith Sowndararajan, Curtis Wilkes, and Yi Wang were especially helpful in discussing research ideas early on in my time at Virginia Tech. And the entire 3DI group has been an excellent source of discussion, support, and feedback over the years. I cannot express enough gratitude to Regis Kopper, Ryan McMahan, and Felipe Bacim for all the encouragement and helpful conversations about research, life, the universe, and everything. And thanks to Bert Scerbo, Karl Huber, Peter Radics, Chreston Miller, Alex Endert, Andy Wood, Cheryl Stinson, and Christopher Andrews for our discussions and collaborations. I also need to extend special thanks Sharon Lynn Chu for making me finish my work and engaging in thought-provoking discussions about the nature of research, academia, and bears.

I would not have been able to complete this work without the facilities of the Virginia Tech Visionarium, and I express my gratitude to Patrick Shinpaugh and Nicholas Polys for their help.

Finally, I thank my family for all their support and for their encouragement to actually graduate.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

A three-dimensional (3D) virtual environment (VE) is a computer-generated, graphical world that supports the perception of simulated 3D space (Sherman & Craig, 2003). Such environments are commonly used for entertainment, training exercises, and online social applications. While the majority of VEs can be experienced through standard displays, such as computer monitors or television sets, immersive VEs often take advantage of additional features to provide a higher-fidelity experience of the virtual space (Sherman & Craig, 2003). For example, stereoscopic displays help users to perceive depths and the structures of 3D objects, tracked head movements allow users to explore the environment using physical movements, and displays supporting high fields of view allow the users to view more of the virtual world at a time.

Many researchers have supported the idea that virtual environments can be used for educational purposes. With the ability to simulate a wide variety of scenarios, VEs have successfully been used for many types of training applications that help users learn new skills or practice procedures. Such systems have been successfully used for vehicular operation (e.g., Bell & Waag, 1998), military training (e.g., Zyda et al., 2003), and medical training (e.g., Grantcharov et al., 2004; Seymour et al., 2002).

Because training scenarios are often designed to simulate real situations, designing such applications is generally fairly straight-forward. On the other hand, for educational applications meant to help teach general concepts and abstract principles, the design must be carefully and creatively constructed in order to support (and not detract from) the learning objectives (C. D. Wickens, 1992; Winn & Jackson, 1999). Many educational VEs have been designed to aid users in these types of conceptual learning. For instance, Dede et al. (Dede, Nelson, Ketelhut, Clarke, & Bowman, 2004) presented a desktop VE designed to help students further their knowledge of science and data analysis. In this application, students learned through working collaboratively to analyze a scenario with ecological and biological problems. As another example, the NICE garden (Roussos et al., 1999) was designed to help students understand plant life cycles and their relationships to agents of nature.

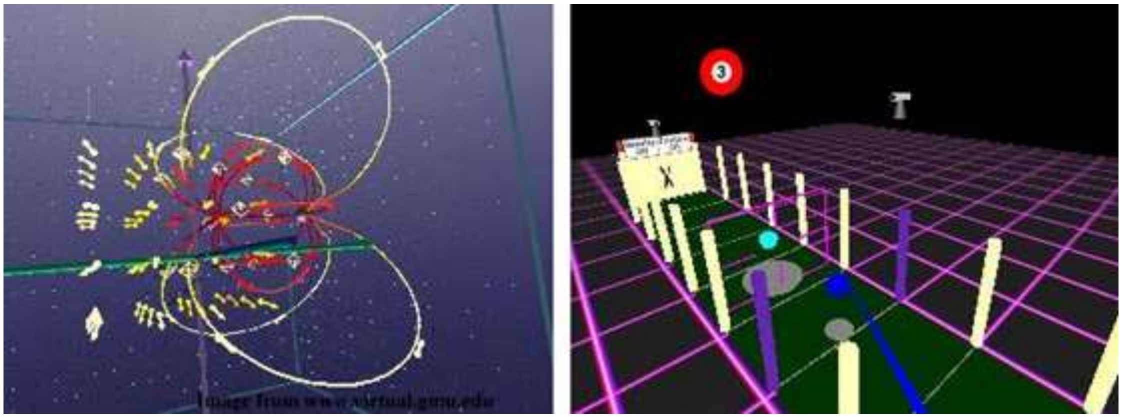


Figure 1. Images of educational VEs from the ScienceSpace projects (Dede, Salzman, & Loftin, 1996). The MaxwellWorld environment (left) allowed students to investigate electromagnetic fields. The NewtonsWorld environment (right) allowed students to interactively learn Newtonian phsyics. Images from (Dede & Loftin) used with permission from C. Dede, 2013.

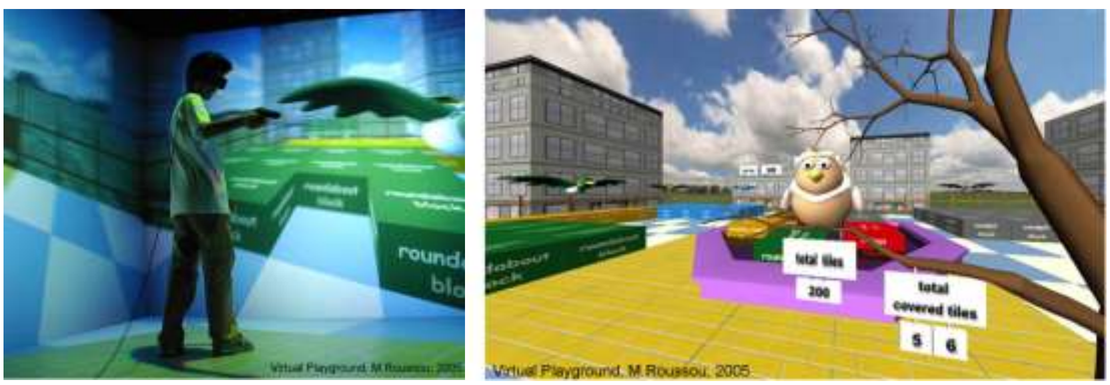


Figure 2. Images of the Virtual Playground for learning mathematical fractions from (Roussou, Oliver, & Slater, 2006), used with permission from M. Roussou, 2013.

It has also been suggested that VEs have great potential for learning complex concepts due to their high levels of interactivity (e.g., Salzman, Loftin, Dede, & McGlynn, 1996; C. D. Wickens, 1992; Winn & Jackson, 1999). For example, the three immersive VEs of ScienceSpace (Dede et al., 1996) were designed to allow students to explore molecular structures, investigate basic principles of Newtonian physics, and experiment with electrostatic fields (see Figure 1). Through experimental interactions with these systems, students were meant to achieve greater understandings of difficult physics concepts. Also aiming to enhance learning through interactive experimentation, AquaMOOSE 3D supplemented mathematics education by allowing students to control the movements of a virtual fish using parametric equations (Elliott, Adams, & Bruckman, 2002).

Attempting to support problem-solving activities, the interactive exercises of Roussou and Slater's Virtual Playground (see Figure 2) were not only meant to help students to better understand numerical fractions, but also how to think about them when solving mathematical fraction problems (Roussou et al., 2006).

Though a wide variety of educational VEs have been developed, little empirical evidence exists to help researchers and educators determine the effectiveness of these applications. Additional evidence is needed in order to decide whether VEs should be used to aid conceptual learning. Furthermore, if there is evidence that VEs can support learning, then developers and researchers will still need to understand how to design effective educational applications.

While the educational projects described thus far have focused on studying interactive approaches, exploratory discovery, and creative instructional methods, they have all shared the challenge of presenting learners with new information within 3D space. Many VEs have faced this challenge more directly, implementing applications in which information—in the form of text, audio, or graphics—is situated at specific locations in the environment. Such mappings are common in information-rich virtual environments, in which additional information is mapped to particular objects or locations (D. A. Bowman, Hodges, Allison, & Wineman, 1999). For instance, Bowman et al. (1999) presented an immersive, virtual zoo application for habitat design education that allowed users to view textual information coupled with various habitat components spread throughout the environment. Current, commonly-used VEs also employ the same approach. Consider Second Life (Rymaszewski, Au, & Wallace, 2007), a web-based, multi-user, desktop VE that allows users to explore and interact through graphical representations of themselves (known as avatars). Boulos, Hetherington, and Wheeler (2007) describe two Second Life environments, HealthInfo Island and the Virtual Neurological Education Center, that allow users to learn about health and medical information by visiting virtual information displays at various locations within the environment. The information locations are organized with the help of virtual buildings, rooms, and landmarks in the VE. Such spatial organizations could potentially aid learning by supporting spatial indexing—allowing locations to be used as references to information (Pylyshyn, 1989). These spatial mappings provide learners with opportunities to use a variety of spatial strategies to remember or relate various pieces of information.

Despite the many VEs that present information in 3D space, much is unknown about the effectiveness of such presentations. Greater knowledge of how to design such presentations is needed in order to improve the effectiveness of educational VEs. Additionally, researchers have not investigated what approaches learners use to help learn new information from 3D spatial representations, which is an important component of understanding how to design VEs. It is unknown how well learners can take advantage of 3D layouts to help understand information. While complex arrangements of information within 3D space can potentially allow for large amounts of information to be presented within an environment, navigation and wayfinding become more difficult. The question of how to design with 3D spatial layouts is complicated by navigational challenges, which can result in disorientation (D. A. Bowman, Koller, & Hodges, 1997).

Figure 3. Images from a section of Health Info Island in Second Life from (Norris, 2010). In the left image, information displays can be seen along a path on the ground. The right image shows an aerial perspective of the information space. Images used with permission from J. Norris, 2013.

Further complicating the issue are the details regarding what types of displays and input devices are used for educational VEs. Compared to desktop displays, more immersive VE systems often provide display features (e.g., stereoscopy, increased field of view) that support improved perception and understanding of spatial information (Schuchardt & Bowman, 2007; Ware, Arthur, & Booth, 1993; Ware & Mitchell, 2005). If learners do employ spatial strategies to help learning in VEs, will display features impact the effectiveness of these applications?

Cognitive processing tasks can also be affected by the interaction techniques used to control navigation (Zanbaka et al., 2004). Consequently, design criteria for spatial presentations may depend on the features of the VE's supported interaction techniques, as more immersive VEs often allow more familiar, natural interaction methods for view control, such as real, physical walking or rotation of the head and body. While prior research has shown that such physical cues improve the ability to maintain orientation and understanding spatial layout in a VE (Chance, Gaunet, Beall, & Loomis, 1998), it is unknown how these effects will influence how learners use spatial information layouts.

The research plan presented in in this dissertation investigates these issues in order to further the knowledge of how to design VEs to support learning. The research includes six studies (five controlled experiments and one case study) to investigate how spatial information presentations affect learning effectiveness and learner strategies. This investigation includes consideration for the complexity of spatial information layouts, the features of display-systems that could affect the effectiveness of spatial strategies, and the degree of interactive control for accessing information. Based on the results of these studies, we developed a set of design guidelines for developing VEs for learning-related activities. By considering factors of virtual information presentation and characteristics of display-systems, our guidelines support design decisions for both the software and hardware required for creating effective educational VEs.

1.2 Concept Definitions

In this section, we define several terms that are important to the discussion of our research of educational VEs and the use of space. We define a *virtual environment* (VE) as a computer-generated, graphical world that supports the perception of simulated 3D space. This definition is based on the description by Sherman and Craig (2003), though we do not limit VEs to environments viewed only through a first-person perspective; that is, we will include applications that allow any type of viewing of simulated, 3D space, including those involving virtual characters. VE systems involve a user interacting with a virtual, 3D world, but this is done through real, physical interactions with devices and displays. Thus, several different "spaces" are involved in VEs. For clarity, we provide definitions to distinguish between display surface, physical space, and virtual space.

Display surface: The physical surface on which virtual objects are viewed (e.g., a screen or monitor).

Physical space: The region of real-world, 3D space physically occupied by the display surface and the user(s) interacting with the VE.

Virtual space: The space available in the synthetic environment displayed by a VE software application, regardless of the size or shape of the physical display surface.

The virtual space of the VE application is viewed on a display surface, and the display surface is contained within the physical space with the user. With these definitions, it is clear that the size of the virtual space is independent of the dimensions of the physical space or display surface. Because the virtual space must be viewed on the display surface, there must be some method to map the virtual space to physical space. In order to view more virtual space than can be viewed at one time on a display surface, the virtual space must be re-mapped to the display surface. For instance, using a standard computer monitor, how could you view the 360 degree area of virtual space surrounding your current location within a VE? Only a portion of the virtual space would be viewable on the monitor at a time. To rotate your view of the virtual space, a different portion must be mapped to the monitor's display surface, providing a different view.

Here, we define several terms to clarify how the concepts of spatial mapping and navigation relate to the use of space in a VE.

Spatial mapping: The function defining how points in virtual space correspond to points in physical space.

Spatial fidelity: How closely the spatial mapping of a virtual environment matches a one-to-one correspondence between virtual and physical space.

i. A system with *high spatial fidelity* allows users to perceive the virtual space within the physical space surrounding them. This allows control of the view of virtual space through natural, physical movements (e.g., walking, physical rotations of the head or body), as done in the real-world.

ii. A system with *low spatial fidelity* requires users to use low-fidelity interaction techniques (e.g., key/button presses, joystick movements) to control the view of the virtual space, adjusting the mapping of virtual space to physical space.

Navigation or *view control*: The act of changing the user's view of the virtual space. We consider navigation to include physical movements of the body or eyes, as well as low-fidelity interactions (e.g., key/button presses, joystick movements) that adjust the mapping of virtual space to physical space, as these all affect the perception of the virtual space.

While navigational control always affects the view of the virtual space, it may or may not require a change in the spatial mapping, depending on the level of spatial fidelity. Again, consider the example of viewing 360 degrees of a virtual space. In this case, a standard computer monitor would be considered to have low spatial fidelity because the user has to depend on a re-mapping of the virtual space to the physical space rather than being able to physically turn to view the surrounding space. On the other hand, consider a system with high spatial fidelity—a display with screens completely surrounding the user. In this case, the user can physically turn around to view a different portion of the virtual space without a re-mapping, as that portion of the virtual space is already mapped to a display surface.

Naturally, the amount of navigation and re-mappings will depend on the complexity of the environment, as more complicated spatial arrangements require more navigation to view the entire space. For example, an environment that requires users to translate and rotate within 3D space is more complicated than an environment that only requires rotation. Because our research is concerned with how information is presented and viewed within educational VEs, we define the following terms to help describe differences in information presentations.

Spatial information presentation: Displaying different pieces of information at specific locations in virtual space.

Degrees of Freedom or *DOF*: Pertaining to navigation, we will use *DOF* to refer to the number of independent dimensions of movement within a virtual space. For example, translation (without rotation) along a 2D plane is two-DOF—one degree of movement along each of the two axes. Full view control within a 3D space allows six-DOF—one degree for translation along each of the three axes, and one degree for rotation around each of the three axes.

Spatial layout complexity: The complexity of the distribution of information locations in a spatial information presentation, as determined by the DOF of navigational control required to view all information as intended (i.e., viewed through comfortable and useful perspectives). For the purposes of this proposal, low spatial layout complexity will correspond to the need for one DOF, moderate complexity corresponds to two DOF, and a high layout complexity will require at least three DOF. A presentation requiring no spatial navigation lacks a spatial layout.

Note that our use of *spatial information presentations* is concerned with the distribution of information at locations, and does not account for the representation format of the information (e.g., textual/graphical or visual/auditory). For convenience throughout this document, we often use the term *spatial presentation* as shorthand for spatial information presentations. Similarly, it should be noted that a *non-spatial presentation* will refer to a presentation that does not distribute information at different locations; such terminology does not inform of the type of information representation.

1.3 Research Questions

Though it has been proposed that VEs have the potential to support learning activities, further knowledge of how 3D applications support learning is needed in order to understand how to effectively design educational VE applications. Additionally, it is unclear how to design learning-based applications to take advantage of the high amount of available space and enhanced spatial cues offered by more immersive systems. If spatial representations are effective learning aids, will it be beneficial to spatially map information to locations in the VE? What factors affect the effectiveness of such a mapping? Further investigation of these questions is needed in order to understand how to develop useful spatial information presentations. Our research aims to address these issues by investigating how spatial information presentations affect learning in VEs. Our goals are to improve the current understanding of how learners utilize spatial mappings and to develop a set of guidelines for the design of learning-based applications.

Q1) How do spatial information presentations in virtual environments affect learning?

Motivated by past work regarding the spatial mapping of information to locations, we will investigate how spatial information presentations, in which information items are displayed in specific locations in virtual space, affect learning. By evaluating performance on cognitive tasks and investigating the strategies that learners employ when provided with spatial presentations, we strengthen the understanding of how to design applications that take advantage of spatial mappings to support efficient learning.

Q2) How does spatial layout complexity affect learning using spatial presentations in virtual environments?

Increasing the layout complexity in spatial information presentations could increase the number of unique spatial mappings of information to locations, but it is unclear how this will affect the learner's ability to manage this complexity. Does increasing the spatial layout complexity hurt or increase the usefulness of the spatial information presentation? How does the utility of linear arrangements of information compare to that of more complicated presentations?

Q3) Do the effects of spatial information presentations on learning depend on the spatial fidelity of the system?

Systems with high spatial fidelity, such as immersive virtual reality systems or large displays, allow users to navigate virtual space using a greater amount of natural, physical, bodily movements—such as physically walking or rotating. But these systems are often more costly than systems with low spatial fidelity (e.g., a laptop computer). Does the level of spatial fidelity affect how learners use spatial information presentations? Is performance affected?

Q4) How does the level of user control in viewing information layouts affect learning?

Automatic view control leaves a viewer unable to influence the navigation of information. Interactive navigation allows learners to control the order and duration of information exposure, but at the cost of additional actions that must be performed during the learning tasks. Further, the complexity of full interactive control is greater for navigating high-complexity spatial layouts. How does this level of control affect the effectiveness of spatial information layouts? Could partial levels of control balance the tradeoffs between purely automated and fully manual modes of navigation?

Q5) How do landmarks and environmental detail affect learning with spatial information presentations?

Supplementing information locations with additional imagery can affect perception of a location's context, and additional visuals can also serve as landmarks to make locations more easily recognizable or memorable. On the other hand, extra visual content could overwhelm users or distract from the learning activity. Does supplementing information locations with visual detail influence the way users think about or access locations? Does environmental detail influence the effectiveness of spatial information presentations?

It is difficult to precisely determine whether environmental detail and supplemental visuals will positively or negatively affect learning because the effect likely depends on the nature of the added details. Nevertheless, this work attempts to investigate this issue. In an effort to avoid problems with complicated or overwhelming visual content, our work only uses simple textures and 3D models. Additionally, we focus on environmental detail at information locations.

1.4 Hypotheses

In this section, we describe our hypotheses based on the previously presented research questions.

H1) Presenting information with spatial, positional mappings improves learning by better supporting strategies that take advantage of spatial indexing.

We hypothesized that spatial information presentations will affect the methods or strategies that learners use for learning information. We expected that these augmented strategies will help learners to improve their performances in learning activities.

H2a) With spatial information presentations, moderate layout complexity will result in greater learning improvements than low layout complexity.

H2b) With spatial information presentations, high layout complexity is less helpful than moderate layout complexity.

While we expected spatial information presentations to improve learning performances (H1), we hypothesized that this effect is dependent upon the spatial layout complexity of the presented information. We expected that a moderate layout complexity will provide more benefits than a low layout complexity because the benefits of added spatial cues will outweigh the costs of the increased challenges with navigating and maintaining orientation. For high layout complexities, we expected these difficulties to outweigh the benefits of spatial cues, causing presentations with moderate layout complexity to support better performance than those with high layout complexity.

H3a) With increased spatial fidelity, spatial information presentations will provide greater learning advantages.

H3b) Increased spatial fidelity will have greater effects on learning performance for spatial presentations with higher levels of layout complexity.

Compared with display systems with lower spatial fidelity, we hypothesized that systems that offer high spatial fidelity will help users to more effectively use spatial information presentations with complex layouts due to the addition of proprioceptive cues and support for intuitive, physical movements for view control. We hypothesized that the impact of these features will be greater for more complex layouts, which require more complex navigation.

H4a) Fully manual view control is superior to automated view control with low and moderate levels of layout complexity.

H4b) Partially-automated view control is superior to fully-manual view control for high levels of spatial layout complexity.

With low and moderate levels of spatial layout complexity, we expect that full, interactive view control will help learners to more effectively use a spatial information presentation by controlling the order and duration in which information is viewed; however, due to the complexity of navigation required to view all information within a presentation with high layout complexity, we expected that partially-automated view control will be better than manual control for high-complexity layouts.

H5) The addition of simple environmental detail to information locations will improve learning outcomes with spatial information presentations.

We expect that the addition of simple visuals to information locations will make the locations more memorable or logically meaningful to the associated information. Thus, we hypothesize that this effect will lead to better learning outcomes.

1.5 Research Approach

In this section, we discuss the scope of the research topic and we provide an overview of the approach used to address our research questions. As we will explain in Chapter 3, the focus of this work on spatial information presentations has been narrowed down within the larger problem space of studying educational VEs. However, even after establishing this focus, the study of spatially distributed information is complicated by a number of interrelated factors (e.g., interactivity, environmental detail, organizational design) that all work together in complex educational systems. To manage this complexity within a controlled experimentation approach, we designed studies to consider multiple factors together in an attempt to learn about more realistic implementations of spatial information presentations. But we also limit the scope of this work to focus on a smaller subset of factors of spatial information presentations. Further, rather than focus on a single cognitive exercise or educational lesson, our research approach studies a variety of different cognitive tasks in an effort to yield more generalizable results that could be applicable to a range of learning tasks. The chosen method can be seen as a survey approach to studying how spatial information presentations affect learning activities. Rather than incrementally drilling down on how one specific design factor affects one specific task, we expected that the investigation of several interrelated factors within a breadth of cognitive would prove more useful to a larger body of researchers.

1.5.1 Scope

i Evaluating learning

The evaluation of learning is a challenging problem and the ideal methods for the measurement of conceptual comprehension are not agreed upon (M. M. Kennedy, 1999; Stasz, 2001). Bloom, Krathwohl, and Masia (1956) and Krathwohl (2002) explain how knowledge can be considered in terms of different levels of understanding and mastery. For example, knowledge of facts, knowledge of how to perform tasks based on learned methodology, and knowledge of how new information fits related to previously learned information can be thought of as different levels of learning. Different pedagogical approaches can be used depending on the types of educational objectives instructors hope to achieve (Krathwohl, 2002). Similarly, different types of assessments can be used for evaluations, though it is uncertain what evaluation methods are the best for different situations (Kane, Crooks, & Cohen, 1999; M. M. Kennedy, 1999). Wiggins and McTighe (2005) organize different facets of understanding that are closely tied to methods of assessment (including explanation, interpretation, seeing perspective, demonstrating empathy, and recognizing self-knowledge).

Because learning is such a complicated topic, we are considering a broad view of its meaning in our investigation. The term "learning" may refer to the ability to recall information that was not known before an activity, the ability to understand or relate the presented information to other information, or the ability to use the presented information to complete a task or to create a new piece of information. For our purposes, we will consider learning to occur when an individual gains new knowledge of the presented information. Rather than directly attempt a complex evaluation of conceptual learning, we will simplify the process by using a variety of cognitive processing activities, including memorization, problem solving, and understanding tasks.

These tasks and evaluations will be designed based on Krathwohl's revised version of Bloom's Taxonomy (Krathwohl, 2002). Serving as a framework for organizing and understanding the different types of learning, Bloom's Taxonomy of Educational Objectives (Bloom et al., 1956) ordered cognitive learning into six levels: knowledge, comprehension, application, analysis, synthesis, and evaluation.

Krathwohl's revised version distinguishes two dimensions of learning: the knowledge dimension and the cognitive processes dimension. The knowledge dimension of the taxonomy (shown in Figure 4) organizes the types of knowledge to be learned into four categories: factual, conceptual, procedural, and metacognitive. Our research will focus on factual knowledge, based on specific facts and details presented through the VE, as well as conceptual knowledge, which is based on learners' abilities to relate pieces of information to other elements and to logically organize the information.

The cognitive process dimension of the revised taxonomy (Figure 4), which is very similar to Bloom's original taxonomy (Bloom et al., 1956), organizes six categories of cognitive processing: remember, understand, apply, analyze, evaluate, and create (Krathwohl, 2002). For our research, we primarily focus on the processes of remembering, which includes recognizing and recalling information, and understanding, which includes interpretation and inference in order to make meaning of information. Our analyses of understanding includes consideration for multiple facets of understanding, based on those described by Wiggins and McTighe (2005), which are summarized in Table 1.

Knowledge dimension	**Cognitive process dimension**
A. Factual Knowledge – The basic elements that students must know to be acquainted with a discipline or solve problems in it a. Knowledge of terminology b. Knowledge of specific details and elements B. Conceptual knowledge – the interrelationship among basic elements within a larger structure that enable them to function together a. Knowledge of classifications and categories b. Knowledge of principles and generalizations c. Knowledge of theories, models, and structures C. Procedural knowledge – how to do something; methods of inquiry, and criteria for using skills, algorithm techniques, and methods a. Knowledge of subject-specific skills and algorithms b. Knowledge of subject-specific techniques and methods c. Knowledge of criteria for determining when to use appropriate procedures D. Metacognitive Knowledge - Knowledge of cognition in general as well as awareness of knowledge of one's own cognition a. Strategic knowledge b. Knowledge about cognitive tasks, including appropriate contextual and conditional knowledge c. Self-knowledge	1.0 Remember – retrieving relevant knowledge from long-term memory 1.1 Recognizing 1.2 Recalling 2.0 Understand – determining the meaning of instructional messages, including oral, written, and graphic communication 2.1 Interpreting 2.2 Exemplifying 2.3 Classifying 2.4 Summarizing 2.5 Inferring 2.6 Comparing 2.7 Explaining 3.0 Apply – carrying out or using a procedure in a given situation 3.1 Executing 3.2 Implementing 4.0 Analyze – breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose 4.1 Differentiating 4.2 Organizing 4.3 Attributing 5.0 Evaluate – making judgments based on criteria and standards 5.1 Checking 5.2 Critiquing 6.0 Create – putting elements together to form a novel, coherent whole or make an original product 6.1 Generating 6.2 Planning 6.3 Producing

Figure 4. A summary of Krathwohl's revision of Bloom's Taxonomy of Educational Objectives (Krathwohl, 2002).

Facet of Understanding	Achievement
Explain	Provide thorough, supported, and justifiable accounts of phenomena, facts, and data.
Interpret	Tell meaningful stories; offer apt translations; provide a revealing historical or personal dimension to ideas and events; make it personal or accessible through images, anecdotes, analogies, and models.
Apply	Effectively use and adapt what we know in diverse contexts.
Have perspective	See and hear points of view through critical eyes and ears; see the big picture.
Empathize	Find value in what others might find odd, alien, or implausible; perceive sensitively on the basis of prior direct experience.
Have self-knowledge	Perceive the personal style, prejudices, projections, and habits of mind that both shape and impede our own understanding; we are aware of what we do not understand and why understanding is so hard.

Table 1. A summary of the six-faceted view of understanding (Wiggins & McTighe, 2005). Used under fair use, 2013.

ii Spatial fidelity

In our investigation of spatial information presentations, we include consideration for the complexity of spatial information layouts, the level of spatial fidelity, and the degree of interactive control for accessing information. We posit that these factors are tightly coupled in determining the effectiveness of spatial information presentations; however, we limit our scope to exclude detailed analyses of several other factors.

For example, the level of spatial fidelity depends on how the virtual space of a VE is mapped to the physical space surrounding the user. Spatial fidelity is largely dependent on the visual components of a system's *display fidelity*—the extent to which our perception of the VE matches how we perceive real-world environments—because these components directly affect how the virtual world is presented on the display surface within the user's physical space. Similarly, spatial fidelity is also determined by how users must interact to view the virtual space. That is, are users able to use physical bodily movements to view the virtual space, as is done in the real world, or do they have to use a less natural form of interaction, such as joystick or mouse control? This becomes an issue of the VE's *interaction fidelity*—the degree that the interaction technique matches the real-world interaction method that would be used to achieve the same goal. Travel techniques with lower interaction fidelity require a greater number of re-mappings of the virtual space to the user's physical space.

Though a VE's spatial fidelity is determined by both its visual display fidelity and its navigational interaction fidelity, for this research we are primarily interested in their combined effect on the perception of the virtual space. As such, we are taking a more holistic view of VE systems, and our studies do not focus on how individual components of display fidelity or interaction fidelity affect the use of spatial information presentations.

iii Information organization

The effectiveness of spatial information presentations undoubtedly depends on how the information is organized in space, but determining an ideal organization or presentation order depends on the specifics of the information and learning objectives. While we feel that improving layout organization techniques is an important topic, further investigation of how users take advantage of spatial information presentations is needed before addressing organizational challenges for 3D spaces. Still, due to the close relationship between spatial layout and information organization, our work does include some consideration for organization. However, we leave detailed investigation of this topic outside of the scope of our work.

iv Environmental detail

Environmental details and landmarks could affect the effectiveness of spatial information presentations, as they could affect how well users are able to navigate spaces or assign meaning to locations. While we have included partial consideration for environmental details in our study, the specifics for preferred choices of details may depend greatly on the learning task and user preference. As such, we do not provide a thorough investigation of different types of environmental detail (as this is not our focus), but we do present recommendations focusing on simple visuals and landmarks at information locations.

1.5.2 Approach Overview

The research plan includes an analysis of the problem space, followed by five empirical studies to investigate how spatial information presentations affect learning effectiveness and learner strategies. As we completed these experiments, we formulated design principles to support effective spatial information presentations. In order to validate these principles, we applied them in the development of an educational VE designed to support a real learning exercise. After an analysis of this design process and the study results, we developed a set of design guidelines for developing VEs for learning activities. Below, we provide an overview of this approach and explain how it will address our research questions.

i Creation of an initial description of the problem space

Following an analysis of the previous research regarding educational VEs, we organized a preliminary description of how the specific problems we are addressing fit within the greater scope of the problem space. We describe the portion of the problem space the proposed work is attempting to cover, as well as the areas that we will be unable to address. This description is presented in Chapter 3.

ii Five experiments with various learning tasks

This step includes five experiments involving a variety of learning tasks.

a. Experiment I: The effects of spatial information presentation on memorization performance.

The main purpose of this experiment was to help address Q1, investigating how spatial information presentations in virtual environments affect learning performance and strategies. Additionally, this experiment partially addressed Q5, studying the effects of additional environmental imagery. This experiment relied on a memorization task as a simple type of learning activity. This experiment was done in a setup with high spatial fidelity. We provide a detailed report of this experiment in section 4.2.

b. Experiment II: The effects of spatial information presentation on problem solving performance.

The purpose of this experiment was to build on the findings of Experiment I, helping to further address Q1, which is concerned with how spatial presentations affect learning in VEs in general. In this experiment, the complexity of the learning task was elevated above that of the memorization task of Experiment I; a problem-solving activity is used as the task. This experiment was done in a setup with high spatial fidelity. Experiment II is further explained in section 4.3.

c. **Experiment III: The effects of spatial information presentation and interactive viewing on learning.**

Building off the conclusions of Experiments I and II, the third experiment compared learning effectiveness using manual and automated types of viewing. Additionally, we varied layout complexity with low and moderate levels. While this experiment provide furthered insight into Q1 (investigating, in general, how spatial presentations affect learning in VEs), its main purpose was to begin to address Q2 (concerned with the effects of spatial layout complexity) and Q4 (concerned with the level of navigational control). The task for this experiment emphasized understanding, though also included memorization. The test application used 2D graphics on a large-display system to gain a conceptual understanding of how space and interactivity affect cognitive processing in spatial displays. This experiment was done in a setup with high spatial fidelity. Chapter 5 provides a more detailed description of this experiment.

d. **Experiment IV: The effects of interactive view control and environmental detail on learning with spatial information presentations.**

The purpose of this experiment is to investigate whether or not the findings of Experiment III (based on a 2D graphical display) also apply to 3D virtual environments. This experiment addresses Q2 (concerned with the effects of layout complexity) by providing data on how people use a relatively simple layout but within a 3D VE. The experiment also compares automatic and manual travel methods, contributing data towards Q4 (concerned with the level of navigational control). Additionally, the study was designed to collect information about environmental detail (Q5) by comparing a relatively empty version of the VE to the same environment with supplemental visuals placed at information locations. More details about Experiment IV can be found in Chapter 6.

e. **Experiment V: Considering the degree of view control and spatial fidelity for spatial information exploration.**

This experiment further addresses Q4 (concerned with the level of navigational control), comparing the effect of partially-automated view control with either fully-interactive or fully-automatic levels of control. In addition, the study compares high and low levels of spatial fidelity, contributing towards addressing Q3. To broaden our research to account for other forms of spatial information presentations, this study uses a data analysis task with location-contextualized scientific information visualization. We present this experiment in Chapter 7.

iii Case Study: Applying design principles to the development of a virtual environment for history education

After aggregating design principles from the previously described experiments, we refined these principles through the development of an educational VE that focuses on a real learning activity. The application was designed around helping users to learn about the causes of the First World War. We developed both desktop and CAVE versions of the application, and we considered numerous design factors that helped us to gain greater insight into spatial information presentations and all of our research questions. After the design and implementation of the application, we conducted a small user study to help evaluate the design principles before preparing our final design guidelines. We discuss the case study in more detail in Chapter 8.

iv Development of design guidelines

Based on the findings of the experiments and case study, this step involved the formulation of design guidelines for spatial information presentations to support cognitive processing tasks. The guidelines include considerations for layout complexity and organization, view control, environmental detail, and spatial fidelity.

v Revision of the problem space description

Based on insights discovered throughout the scope of this work, we revisited our description of the problem space and our explanation of how our work fits within the larger body of research in educational VEs.

1.6 Contributions

1) We provide a description of the problem space to help organize the research space for learning-based 3D environments. This will allow other researchers to see how this work fits into the existing body of research in educational VEs and reveal what areas could most benefit from further investigation.

2) We add to the conceptual and scientific understanding of the role of space and navigation for learning activities through empirical evidence collected from five experiments, contributing to the disciplines of psychology, education, and human-computer interaction. Our results and analyses provide further insight into: (a) the effects of display and software factors on performance in cognitive processing activities, and (b) the strategies employed by users in cognitive processing activities.

3) We provide design guidelines for developing spatial information presentations. These guidelines are based on empirically-gathered evidence and refined through their application to the development of a real application. The generated guidelines include considerations for: (a) the design of the virtual world, based on the concepts of spatial layout complexity and degree of interactive control, and (b) properties of the display systems used for the VEs, based on the analysis of the effects of spatial fidelity.

2 Literature Review

2.1 Learning and Information Processing

Evaluating learning can be complicated, as learning itself is a complex concept with multiple interpretations. The goals of learning activities vary, with the target level of material mastery depending on any number of factors (e.g., available time, activity cost, amount of knowledge needed to perform a task, level of educational institute). Serving as a framework for organizing and understanding the different types of learning, Bloom's Taxonomy of Educational Objectives (Bloom et al., 1956) orders cognitive learning into six levels: knowledge, comprehension, application, analysis, synthesis, and evaluation. Through this ordering, the earlier levels were meant to represent simpler levels of mastery, while achieving the higher objectives meant a more mature mastery of the subject material (Krathwohl, 2002). For the purposes of our research, we observe a broad view of learning, considering multiple levels, but focusing more heavily on the foundational levels that are essential for achieving the higher levels of mastery. As such, in its simplest sense, we consider learning to be the achievement of new knowledge of presented information. That is, learning occurs when information that was in some way contained and represented in a computer system can be recalled or applied without the presence of that information presentation.

With this view, we must be concerned with how individuals process, store, and retrieve information. Helping to describe this psychological process, Wickens' model of human information processing (C. D. Wickens & Hollands, 2000) breaks down this process. In this model, information enters the system from the environment in the form of sensory stimuli (such as sounds or imagery). If attention is given to those incoming stimuli, they will be perceived and interpreted with some meaning. Following perception, the information can be stored in working memory for further consideration. While working memory serves only as temporary storage for conscious thinking, information can be stored in long-term memory for extended periods of time without active attention. Information can also be pulled to working memory from long-term memory for active processing.

Schema theory offers an explanation of how information is organized in memory. According to schema theory, a schema is a generic knowledge structure in memory that can be used to determine how to process new information (R. C. Anderson & Pearson, 1984). Piaget (1977) described schemata as complex, internal representations built to explain the experiences and observations in the external world. These internal knowledge structures help learners relate appropriate information, or even make connections between pieces of information that are not explicitly presented together. Schemata provide a means for knowledge to be stored and organized in long-term memory according to how that information is expected to be used (Chi, Glaser, & Rees, 1981). As a generic structure, a schema is a type of abstract knowledge that can be applied to specific situations in our lives, allowing us to use what we learned in past experiences to make sense of objects or scenarios that we have never seen before.

Building upon schema theory, the ACT-R (Adaptive Control of Thought--Rational) theory of learning and cognition supposes that complex cognition is the result of many well-organized, simple units of information accessed together (J. R. Anderson & Schunn, 2000). At the core of ACT-R is the concept that cognition is based on a set of rules, or productions, for determining the correct responses or actions when the corresponding conditions are met (J. R. Anderson & Kline, 1979). Additionally, using the idea of schema abstraction, even if all of the specific conditions of a specific production rule are not met exactly, the rule's response may still be selected in that situation as long as the conditions are close enough to the rule’s conditions.

Schemata are created in long-term memory based on experiences and conscious processing of information within working memory; thus, it is important to support efficient use of working memory to effectively generate useful schemata when learning new concepts. While long-term memory is seemingly unlimited and may store some information for longer periods of time (perhaps minutes for some items and a lifetime for others), working memory is clearly limited. Memory research has found that retention in working memory is generally limited to around ten to fifteen seconds without active rehearsal of that information (J. Brown, 1959; Peterson & Peterson, 1959). Additionally, working memory is generally only able to hold between five and nine pieces of information at a time for items that are stored through verbal encodings (Miller, 1956), though for visual types of information, the capacity may be limited to three or four items (Vogel, Woodman, & Luck, 2001).

This difference due to representation type is an example that supports Baddeley's (1998) theory that different types of information may be handled by different stores in working memory. By Baddeley's model of working memory, humans possess two types of working memory: visuospatial and phonological (1998). The visuospatial memory store (the visuospatial sketchpad) is used for images and spatial information, while the phonological loop is used to maintain verbal or auditory information. Additional research supports this theory, showing that it may be possible to take advantage of both stores to improve task efficiency by not relying on only one information type (e.g., Duff & Logie, 2001; C. D. Wickens & Liu, 1988). Highly related to Baddeley's dichotomy of working memory is Paivio's (1971) dual-coding theory, which supposes that verbal and visual stimuli are processed along separate channels in cognition. When presenting information, it is believed that coupling imagery with verbal information can support redundant coding, which improves information interpretation (e.g., John Robert Anderson & Bower, 1980; Mayer & Moreno, 2002).

Wickens united the concepts of multiple stages of information processing, multiple resources for processing spatial and verbal information, and multiple perceptual channels into a consolidated theory, providing the Multiple Resource Model (C. D. Wickens, 2008). While resources for cognitive processing are limited, mental workload, the demand or strain on these mental resources (Moray, 1979), may be shared among the multiple stores of resources. On the other hand, mental workload will be much higher if the activity places high demand on a single type of resource (C. D. Wickens, 2008). This serves as further motivation to investigate effective methods for representing information. If spatial information can be processed separately from other information, then that other information can be learned without sacrificing available resources. Thus, for complimentary types of information, supplementing spatial information can certainly be beneficial.

2.2 Spatial Information Features

Similar to the theory that information is processed using multiple types of mental resources, it has also been proposed that knowledge items are stored not as single units, but as collections of features. In his study of the memorization of various words, for example, Wickens (1970) noted the importance of relevant "semantic dimensions" of words. Participants were able to use word meanings or categories to aid memorization of the words themselves. Brown and McNeill (1966) presented a similar explanation in their discussion of the "tip of the tongue" phenomenon. This phenomenon refers to the situations when we are unable to recall a particular item of interest that we know that we know, but we are only able to recall similar words or ideas. Brown and McNeill suggest that memories of items are organized by their features, and sometimes certain features are able to be recalled individually. Research has also shown evidence that recollection of features can serve as a cue to aid the retrieval of associated information (e.g., E. Tulving & Osler, 1968; Endel Tulving & Pearlstone, 1966).

Human cognition processes different information features in different ways. Hasher and Zacks (1979) addressed some of these differences in their discussion of effortful and automatic forms of information processing. While some features of information are learned through effortful processing, requiring attention and intentional learning, other types, such as spatial or temporal information, can be processed automatically, requiring little or no extra attention or demand on available cognitive resources. While a variety of types of information (e.g., images, words, sounds) can be used to cue retrieval, our research focuses on spatial cues.

Mandler, Seegmiller, and Day (1977) provided strong evidence that spatial information is learned automatically, even when the learner is focused on other features. In their first study, university students were asked to study 16 toys distributed among cells of a 6x6 grid. The researchers divided participants into three groups: standard incidental learning, true incidental learning, and intentional learning. In the intentional learning condition, participants were told that they would have to recall the presented items and correctly place the objects within their grid locations. In the standard incidental learning condition, participants were only told they would have to recall the presented items. Lastly, in the true incidental learning condition, participants were only told to study the items so that they could estimate the cost of the toy collection. After studying the objects, the participants were first tested on the recall of object names, and then on the positions of the object locations within the grid. While the results indicated that the accuracy of object placement was well above chance for all groups, analysis showed no significant differences among conditions; however, survey results indicated that many participants in all groups often used locations to aid their learning strategies. In a follow-up study, the researchers repeated a similar experiment, but this time with kindergarten, grade school, and university students as participants. This study confirmed the results of the first study, though university student participants in the true incidental condition performed significantly lower object placement scores than the standard incidental and intentional groups.

Overall, these studies suggest that spatial information is encoded in long-term memory even without intentional focus.

As spatial information is learned automatically, location could be an ideal candidate as a form of redundant coding to reinforce learning and to aid the recall of other information features. By Pylyshyn's model of spatial indexing, locations can be used as references to other information that is not visible (Pylyshyn, 1989). That is, by referencing a location as an index, it is possible to recall the information that was associated with that index. This concept is not limited to the use of real, physical locations. The method of loci, for example, is a memorization strategy that involves mapping pieces of information to different locations (real or imagined) (Yates, 1974). Then, to help recall the information, one imagines visiting the locations. In our research, we are investigating how learners take advantage of virtual space to support similar strategies to improve learning.

Numerous studies have provided evidence that humans do refer to spatial information when recalling information. In one such study, Richardson and Spivey (2000) first showed participants a group of four objects, and then showed the group again with one of the objects missing. When asked to recall details about the missing object, the study found that participants often looked to the location where that object was—even though the relevant information was no longer there. In a similar study, participants listened to a message while a video of a person speaking was displayed in one cell of a 2x2 grid. Four facts were presented in this way—one with a video in each cell of the grid. When asked questions relating to the presented information, participants often looked to the location where the video was displayed for that corresponding message. A follow-up study showed the same results even when displaying a spinning cross in the corresponding cell rather than video of humans speaking. In related research, Love and Southall (1983) asked students to study a 12-page document, presented either in a multiple-page booklet or as a continuous, scrollable document viewable through a single-page window. The following tests revealed better performances by those students with the booklet format. In a follow-up study, the researchers also found that recall improved when they provided participants with the page number and location on the page where the relevant information was printed. In research of menu design, Kaptelinin (1993) concluded that software users rely on locations in lists more than on textual descriptors when selecting menu items. Rather than simply reading the text of the list items, participants selected items based on their positions, relying on a mapping of text and functionality to location. Again, these results demonstrate the value of spatial indexing for data retrieval.

Providing further evidence of the benefits of using spatial information for information processing, research by Hess, Detweiler, and Ellis (1999) found memory benefits when location was used as a redundant indicator. The researchers found performance improvements with their change-tracking task when information was correlated with positions in a grid layout. In this study, graphical icons were used to represent various system states. After viewing a sequence of state changes for an extended period of time, the experimenters would stop the sequence without warning and ask participants to recall the previous states. The study found that participants performed significantly better when the icons for different states were mapped to set positions in a 3x3 grid, rather than when all icons were displayed in the same location. While this study compared a non-spatial layout with a layout with low spatial complexity, VEs can potentially provide much greater complexity. As complex visualizations, our research will evaluate performance differences and investigate learning strategies over a variety of layout complexities.

2.3 Supporting Learning with Spatial Visualizations

Learning is a complex mental activity that involves perceiving new information from external stimuli, relating the new information to previously learned information, and storing the new information in memory. Information presentation should be designed to ease the strain on working memory, which can affect the ability to process information (Sweller, Van Merrienboer, & Paas, 1998). Due to their many successes in making information easier to understand, visualizations are commonly used to help viewers learn new information (Card, Mackinlay, & Shneiderman, 1999). Whether used to represent complex information in a unique way, communicate the meaning of information to others, or serve as a work space for problem solving, the purpose of many visualizations is to help viewers learn something that was not previously known. Discussing the importance of computer-supported data visualization, Card, Mackinlay, and Shneiderman (1999) describe the primary role of interactive visualization as the amplification of cognition. With a similar perspective, Norman refers to visualizations as cognitive artifacts, serving as a means of offloading cognitive processing into the world (Norman, 1991; Zhang & Norman, 1994). Graphical multimedia allows learners to externalize their internal representations of information, reducing the strain on working memory (Scaife & Rogers, 1996; Zhang & Norman, 1994). As a result, more cognitive effort can be used for constructing new internal knowledge structures, sense-making, or working towards other information processing tasks. By this model, new information will be more efficiently understood and encoded in long term memory (Mayer & Moreno, 2003).

Spatial grouping is a common way of visually relating visual representations (Larkin & Simon, 1987). For familiar forms of visualizations, spatial representations are commonly used to effectively present information and support understanding. For instance, in cartography research, MacEachren (1995) showed that spatial positions, compared to other types of visual encoding (e.g., object colors, textures, shapes, or orientations), are especially effective for supporting perception and information processing. As another example, in a study of the design of educational multimedia, Mayer (2003) presented evidence that students learned more effectively and demonstrated more creative problem-solving when related text and images were presented in the same location, rather than separated into different regions.

While such benefits to cognitive processing are apparent for spatial representations in 2D visualizations, significantly less work has investigated how well learners take advantage of spatial representations in 3D virtual worlds. For 3D graphical environments, Robertson, Card, and Mackinlay (1993) suggested that the virtual space available in virtual 3D space can be used as a workspace to hold large volumes of information, and that virtual rooms could serve as a means of organizing that information. In their research using 3D virtual representations to aid science education, Dede, Salzman, Loftin, and Sprague (1999) noted the importance of experiencing the virtual content from multiple locations, through different perspectives. Despite the theoretical advantages of using virtual space to present and organize information, little scientific evidence exists to verify these concepts. Without a strong understanding of the factors influencing effective 3D presentations of information, design methodology is limited.

As an additional problem for designing educational VEs, little is known about how the effectiveness of VEs depends on the specifics of the display system. This is an important issue for deciding what display systems are necessary for educational VEs. Despite the many educational applications that take advantage of immersive technology, only a few projects have attempted to formally quantify the benefits (Mikropoulos & Natsis, 2011). Furthermore, these evaluations were primarily based on comparisons of VE-supplemented education with traditional educational methods (e.g., lectures, real-world activities), but were unable to test for any differences due to the immersive features of the display systems. Johnson, Moher, Ohlsson, and Leigh (2001) worked to integrate VE systems into an elementary school to help students attain greater understandings of scientific concepts, but were unable to find a meaningful method for comparing comprehension to that achieved with traditional instructional methods. Roussou, Oliver, and Slater (2006) compared test results for groups of students using either their Virtual Playground or a physically similar exercise to learn about mathematical fractions, finding no meaningful quantitative differences between their physical and VE exercises. In a separate study, Bowman, Wineman, and Hodges (1999) found evidence for learning improvements for students who used a VE application to aid their classroom study of zoo habitat design, but the researchers were unable to obtain statistical significance due to small class size and poor attendance.

In an attempt to determine how various display characteristics affect learning, the ScienceSpace project (Dede et al., 1996) studied the benefits of groups of immersive features for three different applications. For one of these applications, MaxwellWorld, an application for learning about electric fields, the researchers found significant improvements over more traditional methods (Dede et al., 1999). While this was an important step in evaluation, it was not possible to determine the values of the individual components of immersive technologies. Further, this study did not compare these systems to less immersive, desktop-only VEs. The results of this study did, however, suggest that the ability to view the virtual world through multiple viewpoints—a useful method for achieving a better understanding of the 3D space—was an important contributor to the improvement of learning within the VE. This serves as evidence of the importance of strong spatial cues in certain learning situations.

Further, because VEs with increased levels of visual fidelity provide enhanced spatial cues by leveraging common perceptual abilities used in day-to-day life (e.g., binocular disparity provided by stereoscopy and motion parallax provided by head-tracking with head-based rendering), the high-fidelity, visual features of immersive VEs provide advantages for understanding spatial structures. For example, Ware, Arthur, and Booth (1993) and Ware and Mitchell (2005) found that head-tracking and stereoscopy helped participants to better understand 3D graph structures. Additionally, Schuchardt and Bowman (2007) showed that the addition of stereoscopic vision, head tracking, and increased field of regard (the angular area surrounding the user within which the virtual world can be viewed with physical rotation) improved the understanding of complex, underground cave systems. Further, a study by Arns, Cook, and Cruz-Neira (1999) demonstrated performance benefits of a high-immersion display with multiple large screens over a low-immersion desktop display for structural detection tasks in statistical visualizations.

Similarly, research has shown that such immersive features can improve performance in navigation tasks and general understanding of environmental layout. Research by Chance, Gaunet, Beall, Loomis, for instance, found that the added proprioceptive cues available while walking with a tracked, head-mounted display helped participants maintain orientation and keep track of locations of interest within a VE (Chance et al., 1998). As another example, a study by Tan, Gergle, Scupelli, and Pausch (2004) found evidence that navigation proficiency was significantly better when viewing a VE on a large, projected display rather than on a standard computer monitor.

If spatial representations improve learning and understanding of information, and better understanding of spatial knowledge can improve the effectiveness of spatial representations, these findings suggest that immersive display features could transitively improve learning for certain information presentations in VEs. Studies in information visualization support this claim, showing benefits of high-fidelity visual features for tasks such as analyzing node-graphs (Ware & Franck, 1996) and scatterplot data (Raja, Bowman, Lucas, & North, 2004). Further demonstrating the value of high-fidelity visualizations, Mania, Robinson, and Brandt (2005) found evidence that object recognition was significantly better with higher rendering quality in a study related to the memorization of object information. The current body of work provides little insight into how to appropriately present more complicated or unfamiliar concepts.

Placing greater emphasis on learning new information, rather than understanding and recalling the layout of objects within a VE, Sowndararajan, Wang, and Bowman (Sowndararajan, Wang, & Bowman, 2008) found that users performed significantly better in a procedural memorization task when they used a more immersive VE. The experiment compared a laptop display (low immersion) to a large two-wall projection display (high immersion). Users were shown a medical treatment procedure consisting of multiple steps and asked to view, rehearse, and memorize the procedure before recalling it in the VE. Such a mental activity is a simplified version of conceptual processing involving perception and memorization, but not necessarily understanding.

In a follow-up study, we evaluated recall time and accuracy on a procedure memorization task involving the sequential placement of colored, geometric solids in specific locations (Ragan, Sowndararajan, Kopper, & Bowman, 2010). In this study, we compared performance differences between conditions with varying levels of visual fidelity. Specifically, we varied field of view (FOV; the angular area in the physical world within which the user can see the virtual world at any instant in time), software field of view (the angular area in the virtual world that the user can see at any instant in time, or the FOV of the virtual camera), and field of regard. The overall results indicated that higher levels of sensory fidelity improved memorization performance. We hypothesize that the performance gains can be attributed to the enhanced spatial cues offered by more immersive conditions.

From these past studies, it is apparent that certain aspects of visual fidelity—in particular, field of regard—directly affect the spatial fidelity of a system. A high field of regard helps users to perceive the virtual space within the physically surrounding space, allowing the use of natural, physical movements in manipulate the view of virtual space. This reduces the amount of re-mappings of virtual space to the physical space surrounding the user.

Real-world environments offer the highest possible levels of fidelity, and spatial information presentations certainly exist in the real world. Museums serve as an obvious example of a real-world spatial information presentations. In many ways, designing and organizing museum exhibits is similar to our interests in designing VEs. Museum design challenges also consider factors such as exhibit interactivity, scale, balancing between entertainment and education, and partitioning of space (Allen, 2004). The main difference between museums and VEs, of course, is that physical museums have additional constraints imposed by the real world. As such, museum design includes issues such as physical barriers, gallery entrances and exits, and room sizes (Dean, 1996). Further, while museums are designed to accommodate large groups of visitors, our research focus is on individual learning. But other issues are relevant to both physical and virtual environments. For example, museum design considers floor plans, spatial relationships among objects or exhibits, directionality of exhibit viewing flow, visual balance, balancing object arrangements, balancing between intellectual and more enjoyable content, selection of representation type or media format, and organizational models for presenting content (Dean, 1996). In fact, some of the issues relevant to educational VEs that are beyond the scope of our focus (i.e., information organization and representation) are at least partially covered by existing museum design recommendations. And just as educational VEs are challenged by the need for design evaluation, museums also look to research results for support of design decisions (Allen, 2004). Thus, in many ways, museum design research and VE design can complement each other.

2.4 Dynamic Multimedia and Interactivity

Educational multimedia is often used to present information through the combination of multiple representations, providing the potential to aid learning by allowing learners to experience related information in an integrated context (Levie & Lentz, 1982). It has also been suggested that multimedia with animated components could prove more beneficial than static displays in certain scenarios. Park and Hopkins (1992) described six general learning situations believed to benefit from the use dynamic visualizations, listed below.

(a) demonstrating sequential actions in a procedural task
(b) simulating causal models of complex system behaviors
(c) explicitly representing invisible system functions and behaviors
(d) illustrating a task which is difficult to describe verbally
(e) providing a visual analogy for an abstract and symbolic concept
(f) obtaining attention focused on specific tasks or presentation displays

It was previously believed that dynamic forms of multimedia could always offer further learning benefits over static visualizations; however, following a review of studies of dynamic visualizations for learning, Hegarty (2004) rejected this assumption. Interactivity may serve as a means of eliminating many of the problems of educational multimedia while preserving the benefits of integrating multiple information representations. Rogers and Scaiffe (1997) warned that non-interactive multimedia do not adequately challenge learners to consider multiple models for relationships among the presented informational items, as is desired for more complete levels of understanding; further, this lack of mental integration may only result in "fragmented and superficial learning" (Rogers & Scaife, 1997). Dynamic visualizations deliver a high amount of information within a limited amount of time, but individuals require different amounts of time to process the same information. Interactivity can help by allowing learners to control the delivery of information, easing the demand on working memory (Hegarty, 2004). It has also been suggested that allowing control within complex simulations, interactivity can improve problem solving and creativity (Tennyson & Breuer, 2002). Further, interactivity can increase engagement in the learning process, improving a learner's attention and personal interest in the material (Price & Rogers, 2004).

The rationale for using interactive multimedia to assist learning is largely based on the theory that knowledge is gained through active experience. Piaget proposed that learning was a process of discovery, and that individuals construct and organize mental knowledge structures based on their experiences (Piaget, 1977). In Piaget's theory, such complex, internal representations were built to explain the experiences and observations in the external world. These internal knowledge structures, or schemata, help learners relate appropriate information, or even make connections between pieces of information that are not explicitly presented together. These concepts are foundational for the well-known constructionist learning theory, which emphasizes the need for learners to actively participate in learning activities, rather than the more passive mode of receiving knowledge from given sources (Von Glasersfeld, 1984).

In addition to providing a means for to actively explore information, interactive graphical multimedia allows learners to represent and experience their internal knowledge structures visually (Scaife & Rogers, 1996; Zhang & Norman, 1994). Interactive exploration allows learners to experience information in multiple ways, supporting the construction and testing of various knowledge representations (Price & Rogers, 2004). The goal is to support more meaningful learning through connections with related pieces of information (Mayer & Moreno, 2003), as meaningful material can more effectively be learned and recalled (e.g., R. E. Johnson, 1975; Mayer, 1976). As an example of a form of interactivity yielding quantifiable benefits, research by Bodemer et al. (2004) investigated the effectiveness of integrating text and imagery for understanding the functionality of a simple mechanical system. The results indicated that students better understood the material (though not significantly) when they had to actively integrate the material by moving textual descriptions to the appropriate locations on a diagram; however, the researchers found significant gains in a similar experiment using text and statistical visualizations, rather than the more simplistic mechanical system. While this is an example of a simple form of interactivity, VEs provide the potential for many, more involved forms.

In 3D spaces, even navigation can serve as a form of interactivity that offers the potential for meaningful, controlled exposure to information (Dalgarno, 2002). Additionally, relevant to our interest in spatial information presentations, research has provided evidence that interactive navigation, as opposed to the passive observation of transitioning through a 3D environment, improves memory of object location within the VE (B. M. Brooks, Attree, Rose, Clifford, & Leadbetter, 1999). Depending on the learning strategies used, better spatial knowledge of the environmental layout could improve the effectiveness of spatial information presentations. This motivates our interest in studying how the degree of interactive view control interacts with spatial layout complexity.

Furthermore, while the potential benefits of interactivity described thus far assume interaction techniques requiring relatively small amounts of physical movement (i.e., button presses, and joystick or mouse movements), interactions involving greater physical involvement could yield even greater benefits. This is notable for the discussion of immersive virtual environments, which often support interaction techniques involving relatively higher levels of physical involvement, such as bodily rotations, physical pointing, hand gestures, and walking. For example, Zanbaka et al. (2004) evaluated performance on a task involving the recollection, comprehension, and synthesis of information in a VE. Comparing performance differences due to the navigation technique used, the study found that real, physical walking provided better performance than the other navigation techniques (such as joystick navigation). In our previous study involving the memorization of a procedure, we found that the greatest performance improvements were attributed to increased field of regard, which allowed user to use natural, physical rotation to view the VE (Ragan et al., 2010). These results may be attributed to reduced mental workload while using a more natural, familiar form of view control, but this is not the only benefit of employing physically-based interactions.

It is believed that physical movements and positions are often mapped to external information. Through this *deictic binding*, motor actions and internal cognitive processes can be linked with external sensory information (Ballard, Hayhoe, Pook, & Rao, 1997). Then, for supporting learning, interactivity involving high levels of physical movement can provide the added benefit of motor memory cues to aid memorization and recollection. In a study of the memorization of a sequence of actions, Cohen (1989) found evidence that making physical movements while learning the sequence helped improve participants recall the sequence later. Based on the nature of the types of actions made during the experiment, Cohen also noted that specific types of motor action had little effect on recall, stating that any sequence of corresponding physical actions is equally effective in improving supporting memorization performance. In another study related to memory, Casasanto and Dijkstra (2010) found that physical movement of marbles affected the retrieval of memories of emotions. Additionally, Patten and Ishii (2000) provided evidence that physical interactivity improves the effectiveness of spatial mapping for recall. Their study found that participants were better able to map information to locations when using a tangible system requiring physical movements of wooden blocks, compared to a system displaying virtual graphics and relying on a mouse for interaction.

Because system interaction techniques can influence mental workload and memory, it is important to consider difference techniques supported by the display system. In particular, we are focusing on navigation (or view control) because it is necessary to access different locations and to achieve different views within 3D space.

2.5 Virtual Environment Learning Applications

Following our discussion of the background concepts of learning, space, and interactivity, in this section, we provide an overview of the many types of applications that have been developed to support learning in 3D environments. The presented examples will help us to describe where our research lies within the problem space of research in educational VEs.

VEs have been used for many educational purposes. Many VEs have been designed specifically for training applications to help users to learn new skills or to practice procedures. Vehicle simulations, for example, were the earliest use of virtual environments (F. P. Brooks, 1999). Similarly, medical training systems allow surgeons to practice surgical techniques (e.g., Grantcharov et al., 2004; Seymour et al., 2002). Johnson and Rickel (1997) employed virtual characters to help users learn the steps of procedures, such as operating complicated machinery.

VEs are also used to aid military training to support the learning of concepts, rather than just physically-based skills and procedures. For example, *America's Army: Operations* is a 3D game that allows users to learn about the day-to-day operations of American soldiers and how different weapons handle and fire (Zyda et al., 2003). Other military simulations have been used to help users to strengthen their communication and decision-making skills (Page & Smith, 1998). Similarly, for medical education, Johnsen et al. (Johnsen et al., 2005) also explored the use of virtual characters in a VE to help medical students improve communication and decision-making skills. Medical training applications can also aid other forms of conceptual learning. For instance, Quarles, Lampotang, Fischler, Fishwick, and Lok (J. Quarles, S. Lampotang, I. Fischler, P. Fishwick, & Benjamin Lok, 2008) employed a mixed-reality system, which allowed users to view virtually-displayed objects and information integrated with real, physical objects, to support the conceptual understanding of anesthesiology machinery. This application was used to help anesthesiology students connect their abstract mental models of equipment functionality to the actual workings of the physical, real-world machines. As another form of specialized education, VEs have also been used to educate users about safety issues, such as for mine safety (e.g., Filigenzi, Orr, & Ruff, 2000).

Many applications have also targeted more common topics. For example, many VEs have been designed to support mathematics education. The AquaMOOSE 3D application supplemented mathematics education by allowing students to control the movements of a virtual fish using parametric equations (Elliott et al., 2002). Rousou and Slater's virtual playground (2006) was designed to help students to better understand numerical fractions and to improve strategies for solving mathematical fraction problems. As another example, the Construct3D application showed promise for assisting the learning of geometric structures through interactive, 3D visualizations (Kaufmann, Schmalstieg, & Wagner, 2000).

Educational VEs have also focused on science education. As mentioned earlier, the three virtual worlds of ScienceSpace (Salzman et al., 1996) were designed to allow students to explore molecular structures, investigate basic principles of physics, and experiment with electrostatic fields. As another example, the NICE (Narrative-based, Immersive, Constructionist/Collaborative Environments) garden, was designed to help students understand plant life cycles and their relationships to agents of nature (Roussos et al., 1999). Johnson, Moher, Ohlsson, and Leigh (2001) described a variety of VEs, including those that that allowed students to explore the solar system, examine the anatomy of insects, and inspect the shape of a volcano before and after eruption. Fjeld et al. (2003) described an application that supports chemistry education by allowing students to combine elements to build molecules using a tangible user interface.

In addition to the sciences, educational applications have also been developed to support social studies topics. For example, a VE described by Slator et al. (2001) supported anthropology and archeology education through investigation and problem-solving activities that also incorporated principles of geology and biology. As a similar application, the On-A-Slant Village (Hokanson et al., 2008) was designed to help students learn about Native-American culture through experiences and interactions with virtual characters. In the River City environment (Dede et al., 2004), students could work to integrate historical, social, and geographical knowledge in the critical thinking task of understanding the nature of illness within the virtual city. These applications demonstrate the ability of VEs to incorporate a variety of topics into engaging, educational experiences.

Educational VEs can even be used to support the learning of foreign languages. Rose (1996) detailed an immersive VE designed to help students to learn the Japanese language through both passive and interactive activities involving audio along with 3D visual representations.

Additionally, Dickey (2005) describes a multi-user, 3D environment that allows users to learn about business concepts by navigating to certain locations (see Figure 5). Dickey emphasizes the importance of the application serving as a means of social interaction while providing an environment as context for learning. This is similar to the two Second Life environments that we mentioned earlier, HealthInfo Island and the Virtual Neurological Education Center (Boulos et al., 2007), in which users learn about health and medical information by visiting virtual information displays within the environment (see Figure 3).

While these examples of learning-based VEs by no means constitute an exhaustive list of existing applications, this discussion should provide an overview of the great variety of uses for educational VEs. Applications have been developed to help users learn many different types of skills and information. Application designs vary greatly, as influenced by the specifics of the target material.

Figure 5. A screen shot from the Active Worlds environment for business learning (Dickey, 2005). Image used with permission from M. Dickey, 2013.

2.6 Summary of Related Work

Learning is a complex process involving the perception, interpretation, and organization of information. Our research with spatial information presentations is largely based on the notion that knowledge items are not stored as individual units, but as collections of features (R. Brown & McNeill, 1966; D. D. Wickens, 1970). Relevant to our focus of the use of space, previous studies have provided evidence that spatial features can be learned automatically, without conscious, intentional focus (e.g., Mandler et al., 1977). Combining this theory of automatic spatial processing with the concept of spatial indexing, which is based on the idea that locations can be used to help access other information (Pylyshyn, 1989), we hypothesize that spatial information presentations can be used to support learning in VEs.

While previous studies have attributed cognitive benefits to the mapping of information to locations, (e.g., Hess et al., 1999; Mayer, 2003), little work has addressed this concept within VEs. Though many educational VEs have employed spatial information presentations (Boulos et al., 2007; D. A. Bowman, Hodges, et al., 1999), evaluating the effectiveness of these presentations has been challenging. We will address this challenge with controlled experimentation involving simplified learning tasks.

As a compounding issue, accessing information distributed among multiple locations requires navigation, and research has shown that navigation techniques can affect cognitive processing (e.g., Ball, North, & Bowman, 2007; Zanbaka et al., 2004). Our hypothesis about increased spatial fidelity supporting improved performance is related to these findings, based on the notion that natural, physical forms of navigation are more intuitive, less cognitively demanding, and allow a better understanding of the virtual space. We are also interested in interactions with spatial complexity, as more complex spatial presentations require more complex types of navigation.

Additionally, our research is concerned with the level of interactivity of the navigational methods. While it is believed that some forms of interactivity can support more effective and meaningful learning (R. E. Johnson, 1975; Mayer, 1976; Mayer & Moreno, 2003), it is also believed that other forms detract from learning (Rogers & Scaife, 1997; C. D. Wickens, 1992; Winn & Jackson, 1999). This idea motivates our investigation of how the level of view control affects learning with spatial information presentations.

3 Understanding the Problem Space

Research in educational VEs is a broad topic with many possible approaches for investigation. In this section, we frame our approach and the scope of the proposed research within the larger scope of research in educational VEs. We describe how this work relates to previous research and further distinguish which elements are and are not within the scope of our investigation. With this description, we hope to help further organize the problem space to help other researchers to better understand the rationale for our approach within a greater context. Further, by describing the portion of the problem space that we are attempting to cover, identifying the areas that we will be unable to address, and discussing alternative methodologies, we hope to help others to formulate future research agendas.

Through our review of the literature, we found the body of research in educational VEs to be both large and complex. We feel that clear, focused research questions are important when adding to this body of work. Otherwise, it becomes more difficult for the lessons that are learned to be applied to other projects, and for the findings to be integrated with those of other studies. The presented scheme has helped us to narrow the focus of our investigation and to identify its relationship to previous research.

We describe the place of our research within the problem space with a series of questions. We discuss possible answers to these questions and explain how our investigation fits within this organization. A summary of our description of the problem space and the focus of the proposed research is presented in Table 2.

I. What types of learning do educational VEs support?

When studying applications with learning purposes, the first step is to consider what types of knowledge will be learned. Here, we describe five general types of knowledge: procedural knowledge, factual knowledge, conceptual knowledge, spatial knowledge, and knowledge of physically-based phenomena. The procedural, factual, and conceptual types of knowledge are based on Krathwohl's (2002) descriptions in the knowledge dimension of his taxonomy of educational objectives. We also include spatial knowledge and knowledge of physically-based phenomena as two more knowledge types commonly targeted with educational VEs. Certainly, investigations could target multiple types of knowledge (as many applications commonly do). In the proposed investigation, we are focusing on factual and conceptual types of knowledge.

a. **Procedural knowledge**

Procedural knowledge refers to knowledge of how to perform some task. This includes the knowledge relating to the specific skills needed to complete the task (Krathwohl, 2002). Training VEs are examples of applications that aim to improve procedural knowledge. These include flight simulators (e.g., Bell & Waag, 1998), the applications used for training astronauts (e.g, Loftin & Kenney, 1995), and those used for military-types of training (e.g., Zyda et al., 2003).

b. **Factual knowledge**

This category includes knowledge of facts, details, and specifics of terminology (Krathwohl, 2002). The previously described Second Life environments, HealthInfo Island and the Virtual Neurological Education Center (Boulos et al., 2007), largely focus on supporting this type of knowledge with their embedded information displays.

c. **Conceptual knowledge**

This type of knowledge involves relating pieces of information to other elements, logically organizing various elements of knowledge, and abstracting or applying theories (Krathwohl, 2002). The Virtual Playground (Roussou et al., 2006) is an example of a VE targeting this type of learning, helping students to improve their understanding of the abstract concept of fractions, as well as how this concept applies to a physical representation. The River City VE (Dede et al., 2004) also stressed conceptual learning, helping students to relate elements of historical, social, and geographical knowledge.

d. **Spatial knowledge**

We use this category to describe knowledge based on a spatial understanding, such as knowledge of locations, object structure, or geographical layout. Many training applications, for example, depend on the user’s ability to learn an environmental layout and navigate effectively through that environment (Waller, Hunt, & Knapp, 1998). Mania, Troscianko, Hawkes, and Chalmers (2003) studied this type of knowledge in their study of how display fidelity affected the memory of object locations within a VE. As another example, the

AquaMOOSE 3D (Elliott et al., 2002) coupled conceptual knowledge of mathematics with spatial knowledge through graphical representations of equations.

e. **Knowledge of physically-based phenomena**

As a combination of conceptual and spatial knowledge, we propose this category because of the large number of VEs used specifically to help students understand physical phenomena. The ScienceSpace applications (Salzman et al., 1996), for example, allowed students to explore molecular structures, investigate basic principles of physics, and experiment with electrostatic fields through explorations within virtual space. With their educational applications that allowed students to explore of the solar system, examine insect anatomy, and inspect the shape of a volcano before and after eruption, Johnson, Moher, Ohlsson Leigh (2001) provided similar integrations of spatial representations and conceptual information.

II. What are the possible approaches for studying the potential value of educational VEs?

A variety of approaches are available for studying educational VEs, and the type of approach will significantly affect how the results can be interpreted. For simplicity, we have grouped the possibilities into three categories: ecological evaluation with complete applications, controlled experimentation with complete applications, and controlled experimentation with simplified learning tasks.

a. **Ecological evaluation with complete applications**

For this type of approach, complete applications are developed for a specific educational purpose and evaluated within the real-world setting in which they are intended to be used. Examples of previous projects that fall in this category include the ScienceSpace applications (Salzman et al., 1996), as well as the QuickWorlds, Cognitive Studies, and Virtual Ambients projects by Johnson et al. (2001). Studying the applications within the actual context of intended use could reveal additional insights that might have been missed with highly controlled evaluations. By studying how the application is used in a real learning environment, researchers may be able to hypothesize which features of this particular application provide the greatest educational value or which features detract from that value, providing a basis for following research to test these hypotheses. However, due to the specificity of the complete application, the findings will be less likely to generalize to other applications.

b. **Controlled experimentation with complete applications**

This type of approach also involves complete applications for supporting specific learning goals, but evaluations are conducted through controlled experimentation. Like ecological studies with complete applications, findings from studies in this category may be difficult to generalize due to application specificity. Controlled studies could also miss many qualitative observations gathered through application use in a real setting. On the other hand, the increased level of experimental control could make it easier to scientifically test which features of the application most influcence their effectiveness.

c. **Controlled experimentation with simplified learning tasks**

In this approach, rather than studying a complete application for a specific use, a simplified application can be used for controlled evaluation of the effectiveness of a certain set of features. Such an application may target a simple, generic type of learning activity instead of a practical learning topic. The memorization activity in the study by Bowman, Sowndararajan, Ragan, and Kopper (D. A. Bowman, Sowndararajan, Ragan, & Kopper, 2009), which involved the sequential placement of colored objects in specific locations within a grid, is an example of such a simplified learning activity. Another example is the study of how various navigation techniques affect various cognitive activities (including recollection, comprehension, and synthesis of scene details and information presented in a virtual room) by Zanbaka et al. (2004). Due to the nature of such a learning task, this type of approach is not well-suited for evaluations of application use in a real learning setting. The advantage of such an approach, however, is that the experimental findings with this simplified learning activity will be more likely to apply to a greater variety of real applications. Thus, the abstraction of the learning task provides generalizability. This is highly desirable for cases, such as ours, where the researchers hope to generalize a set of design principles based on the evaluation.

III. **What are the proposed reasons for why VEs could be beneficial for learning?**

For our next step, with our focus on factual and conceptual learning, we consider the possible reasons why VEs could provide educational value. With our approach of controlled experimentation using simplified learning tasks, it will be possible to evaluate the validity of these reasons for the selected types of learning. Based on our review of the literature, we describe the most commonly proposed reasons why VEs could be beneficial for learning. We note that this is not an exhaustive list, but rather an overview of the possible reasons why VEs could prove useful for education. For these reasons, our work will focus on navigation (as a component of interactivity) and the use of space, as they are closely related concepts.

a. **Interactivity**

Interactivity is a commonly suggested reason why VEs could be advantageous for learning (e.g., Dede et al., 1996; C. D. Wickens, 1992). VEs can potentially support a wide variety of types of interaction. Navigation allows learners to view the environment from multiple perspectives and affects the order and duration that objects and scenes are viewed. Organizational types of interactivity could allow users to create or modify external representations of information in a way that is more meaningful to them. Similarly, annotation could allow learners to supplement their own notes within the environment to help them organize or remember key concepts. Additionally, interactive objects could help users to further understand object functionality and purpose. Or, rather than objects functioning individually, inter-object functionalities could allow users to learn how different objects relate or work together as part of a system.

b. **Engagement**

It has been suggested that VEs can provide a more interesting means of learning than more traditional forms of instruction (Salzman et al., 1996). While this could be attributed to the novelty of the experience, learning sessions could also be more engaging due to their interactivity or unique forms of presentation.

c. **Active learning**

Another commonly proposed reason why VEs could provide educational value is that VEs can serve as a vehicle for active learning. Active learning involves doing activities, rather than simply observing examples or listening to lectures (Fink, 2003). It has been suggested that educational VEs can help provide more meaningful, memorable learning experiences (e.g., C. D. Wickens, 1992; Winn & Jackson, 1999). This reasoning is closely related to the proposed benefits of interactivity and engagement.

d. **Collaboration and social learning**

Many applications have touted the collaborative benefits of learning in VEs. Virtual agents may be used to guide students along, providing social context for activities, as done in the Virtual Playground (Roussou et al., 2006) and Johnson and Rickel's (1997) procedural training application. Alternatively, many applications also support learning with other real users, as was done in the River City scenario (Dede et al., 2004), Dickey's (2005) social environment for learning business concepts, and the NICE garden (Roussos et al., 1999).

e. **Multiple representations of concepts**

VEs can provide opportunities for students to learn concepts through unique and varied types of representations. For instance, instead of representing mathematical fractions only as numerical symbols or static graphics, the interactivity of the Virtual Playground (Roussou et al., 2006) provides students with a unique application of fractions in a familiar context. As another example, the NICE application (Roussos et al., 1999) allows students to learn about ecosystems through multiple representations (interactive stories and garden-care activities). The QuickWorlds (A. Johnson et al., 2001) project was also based on the idea of providing supplemental visualizations to help students learn with additional representations.

f. **Use of space**

It has also been suggested that virtual space could be used to support learning. Supporting practically unlimited storage, virtual spaces can hold and organize large volumes of information (Robertson et al., 1993). The MaxwellWorld application of the ScienceSpace project (Salzman, Dede, Loftin, & Chen, 1999), which was shown to provide significantly stronger conceptual understandings of electrostatic fields compared to more traditional instructional methods, allowed students to learn these concepts through interactive explorations within virtual space. The researchers believed that these benefits could be attributed to the ability to manipulate view perspectives or frames of reference within space.

Additionally, the HealthInfo Island and the Virtual Neurological Education Center (Boulos et al., 2007) environments provide locational contexts for learning different kinds of information. Studies have found evidence that spatial indexing can be used to help recall information (e.g., Hess et al., 1999; Richardson & Spivey, 2000). Further, in our previous study with the memorization task involving the placement of colored, geometric solids at specific locations on a grid, we hypothesize that the learning improvements gained with more immersive display features were due to better spatial understanding of the scene (D. A. Bowman et al., 2009; Ragan et al., 2010). These results suggest that VEs can help learners to use spatial strategies to improve their learning.

IV. Based on the reasons selected, what are the primary factors that could influence the effectiveness of educational VEs?

Finally, after narrowing down the major possible topics for investigation of educational VEs, it is necessary to consider the various factors that could influence the effectiveness of the proposed benefits. Here, based on our research focus, we describe the primary factors that we hypothesize could affect navigation and the use of space. Note that this is not an exhaustive list of all related factors, as many other issues could also potentially influence the effectiveness of VEs. We provide the following factors as clear examples that are relevant to our work.

a. **Organizational issues**

Factors in this category are related to how learners perceive orderings and spatial groupings. For example, the order and duration of exposure to different items within a VE could influence the effectiveness of an information presentation. Similarly, though objects may be grouped in many different ways, different learners may prefer different groupings. These individual preferences and the variety of possible organizations could certainly affect how users make use of space when learning in a VE. The concept of layout complexity could also be considered as an organizational issue, as it is related to how items are distributed in space; however, in our investigation of layout complexity, we note that we are focusing on how information locations are distributed, but not on how different informational elements are presented in relation to other pieces of information.

b. **Representation**

How information is represented undoubtedly affects how it is perceived and interpreted. For example, information could be presented through text, numbers, static imagery, 3D models, or animated scenes. Additionally, the effectiveness of these representations could depend on their sizes or their proximity to other representations. Many other issues could be included as representation issues. For visual representations, are appropriate color choices used to support perception? If information is represented as text, is formal or informal language used? Is information presented within bulleted lists or encapsulated within a detailed narrative? Is numeric data represented through numeric symbols or through graphs? These are just a few of the many representation factors that could influence the effectiveness of our information presentations, but we are not focusing on these issues in our research. Our learning activities are based on visual representations involving both text and imagery.

c. **VE Fidelity**

The fidelity of a VE refers to its realism as compared with the equivalent experience in the real world. Multiple factors affect the overall perception of realism. As explained earlier, spatial fidelity, which involves the perception of the virtual space and the interaction within that space, is affected greatly by visual display fidelity and navigational interaction fidelity. *Interaction fidelity* refers to the degree that the technique used to interact in the VE matches the real-world interaction method that would be used in an equivalent real-world scenario. For example, if the scenario involves walking across the street, physical walking will provide a higher level of interaction fidelity than using a joystick to control navigation; however, if the task is to pilot an aircraft, then joystick interaction would be expected to offer higher interaction fidelity than using physical walking to control the aircraft. *Display fidelity* refers to realism of the sensory stimuli provided by the VE. For example, display fidelity could be improved by increasing display resolution, supporting 3D, surround-sound rather than providing audio through a single source, or by increasing the field of view of a visual display. Finally, a VE's fidelity is also influenced by the realism of behaviors within the virtual world. For instance, the realism of the artificial intelligence for virtual characters or how realistically objects obey the laws of physics could affect this *simulation fidelity*. For our investigation, we are not including any evaluation of the effects of simulation fidelity on learning.

d. **Level of Interactivity**

In addition to the fidelity of interaction techniques, other design factors of interactivity could influence the effectiveness of VEs. Departing from the issue of realism, VEs have the potential to vary the functionality of interactive features in interesting and unrealistic ways. One of these design decisions of particular interest for our work involves the level of control given to users. For example, the level of navigational control (i.e., whether view control is automatic or fully-controlled) will affect how users experience the content of the VE.

e. **Number of users**

System effectiveness could depend on how many users are using the VE at a time. Multi-user environments could create opportunities for additional learning strategies that may not be possible for a single user. In a co-located environment, multiple users could work within the same physical space, affecting how that space is perceived and used. Our research is only focusing on single-user VEs.

f. **Individual differences**

People are different. As a few examples, individuals can have different preferences, physical sizes, previous experiences, beliefs, and cognitive capabilities. Any of these differences can affect how much any single user will benefit from an educational VE. Individual differences can also greatly affect the influence of other factors.

g. **Knowledge domain**

In addition to the type of knowledge being learned, the domain or discipline of that knowledge could affect the effectiveness of the proposed benefits. It could be that learners are more likely to use different strategies for learning material from different domains. Thus, results could vary depending on the learning topic (e.g., mathematics, literature, history, language, or biology).

Refining Questions	Our Research
What types of learning do educational VEs support? • Procedural knowledge ★ Factual knowledge ★ Conceptual knowledge • Spatial knowledge • Knowledge of physically-based phenomena	Our research is primarily interested with learning facts and understanding relationships between different informational elements.
What are the possible approaches for studying the potential value of educational VEs? • Ecological evaluation (complete application) • Controlled experimentation (complete application) ★ Controlled experimentation (simplified learning task)	Controlled experimentation with a variety of learning tasks will help us generalize a set of design guidelines, which we will refine with the help of our case study.
What are the proposed reasons for why VEs could be beneficial for learning? ★ Interactivity • Engagement • Active learning • Collaborative and social learning • Multiple representations of concepts ★ Use of space	We are focusing on studying the use of space to support spatial strategies for learning factual and conceptual information. We are also studying navigation, a form of interactivity, as it is closely related to the use of space.
Based on the selected reasons, what are the primary factors that could influence the effectiveness of educational VEs? ★ Organizational issues • Representation ★ VE fidelity ★ Level of interactivity • Number of users • Individual differences • Knowledge domain …	Our work will focus on investigating spatial fidelity, the level of navigational interactivity, and layout complexity, but this will not amount to extensive investigations of all issues related to information organization, VE fidelity, or other forms of interactivity not related to view control.

Table 2. Summary of the problem space. This table explains of how our research fits within the larger body of research in educational VEs. Starred items in the left column indicate items related to our research approach.

4 Experiments I and II: Supporting Memorization and Problem Solving with Spatial Information Presentations

4.1 Summary

We began our research by evaluating performance on cognitive tasks and studied the strategies that learners employ when provided with spatial presentations. Our first two experiments investigate whether users can take advantage of a spatial information presentation to improve performance on cognitive processing activities. This work is reported in a *Virtual Reality* journal publication (Ragan, Bowman, & Huber, 2012). In both experiments, information was presented either directly in front of the participant or wrapped around the participant along the walls of a surround display. In our first experiment, we found that the spatial presentation caused better performance on a memorization and recall task. To investigate how learners use spatial information presentations in higher-level cognitive activities, our second experiment employed a puzzle-like task that required problem solving using the presented information. The results indicate that no performance improvements or mental workload reductions were gained from the spatial presentation method compared to a non-spatial layout for our problem-solving task. The results of these two experiments suggest that supplemental spatial information can affect mental strategies and support performance improvements for cognitive processing and learning-based activities. However, the effectiveness of spatial presentations is dependent on the nature of the task and a meaningful use of space, and may require practice with spatial strategies.

4.2 Experiment I: Supporting Memorization with Spatial Information Presentations

4.2.1 Goals

In our previous work (Ragan et al., 2010), we found that conditions offering higher levels of visual fidelity supported better performance on a procedure memorization task. We hypothesized that participants were able to more effectively take advantage of spatial organization strategies to improve the effectiveness of their memorization strategies, but we were unable to test this claim. A greater understanding of these results is important for applying the lessons learned to designing effective educational VEs.

In the first presented experiment, we follow up on this earlier work by investigating whether or not the performance improvements for a sequence memorization task could be attributed to spatial cues and memorization strategies. The experiment was designed to investigate whether spatial information layouts could be used to support more efficient memorization of information. Closely related to the idea of using spatial locations to aid learning is the issue of how environmental details influence perception of space and the ability to use spatial mapping strategies. To address this issue, we also tested how the presence of landmarks affected performance with spatial and non-spatial distributions of information. Lastly, because spatial perception is influenced by display factors contributing to visual fidelity, we also varied field of view (FOV).

4.2.2 Hypotheses

We hypothesized that providing greater support for spatial memorization strategies would result in better performance for sequence memorization. We hypothesized that information presented in a highly spatial layout would allow better performance than a non-spatial distribution.

Further, based on the results of past studies (D. A. Bowman et al., 2009; Sowndararajan et al., 2008), we hypothesized that a display that offers a greater FOV would better support spatial memorization strategies. Prior studies have shown that higher FOVs can positively affect both memorization (Lin, Duh, Abi-Rached, Parker, & Iii, 2002) and spatial learning (McCreary & Williges, 1998). We hypothesized that users would achieve greater performance when provided a higher FOV with a spatial presentation and that FOV would not make a difference with the non-spatial presentation.

Additionally, we hypothesized that spatial information presentation would more strongly support participants' memorization strategies if the environment afforded clear landmarks that could be associated with the steps of the sequence. Similar to the method of loci, in which memorization is aided by associating information with locations (Yates, 1974), we expected that performance would improve for the spatial presentation if landmarks and perspective cues were provided.

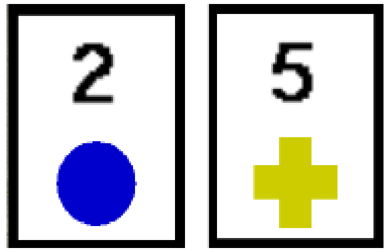


Figure 6. Examples of two cards used in Experiment I.

4.2.3 Task

In this study, participants memorized a sequence of colored objects and an associated number. The objects were common 2D shapes (square, circle, triangle, cross, and star) and the numbers were whole numbers ranging from zero through nine. The shapes were colored red, blue, yellow, green, or black. For each step of the sequence, participants were shown both the object and the associated number together on a card image (see Figure 6). A sequence contained seven cards. Each card was displayed for six seconds before it was removed and the card image for the next step was displayed. Only one card was shown at a time. Participants were asked to memorize the sequence of colors, shapes, and numbers in order. Thus, the two steps for the corresponding sample cards shown in Figure 6 would be:

Step 1: blue, circle, 2
Step 2: yellow, cross, 5

The cards were presented inside a four-screen CAVE™ projection display using 1280x1024 Electrohome CRT projectors with each rear-projected wall measuring 10' wide and 9' high and a front-projected floor measuring 10' by 10'. The images were rendered with 3D perspective cues, but no stereoscopy or head tracking was enabled. After viewing the sequence twice, participants were asked to step out of the CAVE environment and were seated in a chair facing away from the display system. Participants were then asked to verbally state the color, shape, and number for each step of the sequence.

Performance was evaluated based on accuracy and time taken to report the sequence. Accuracy was scored by counting the number of correct components (color, shape, or number) for each step of the sequence. One point was awarded for each correct component given for a step in the sequence. Because each step had three possible components and the sequence had seven steps, the highest possible score was 21. Zero was the lowest possible accuracy score. For simplicity and fairness across conditions, this scoring scheme did not adjust for special circumstances, such as when a missed step in the sequence might shift the subsequent card components.

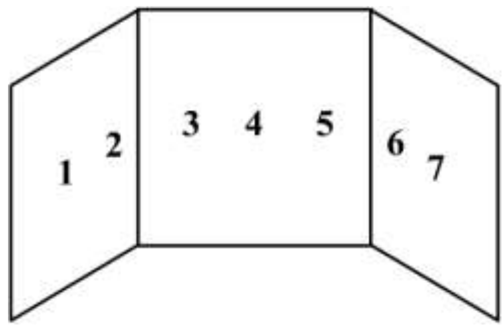


Figure 7. For the spatial presentation condition, each card of the sequence was displayed in a different location across three projection walls, one card at a time. For the non-spatial layout, every card was displayed at position four.

4.2.4 Experimental Design

To test our hypotheses, we controlled three independent variables: presentation layout, presence of landmarks, and FOV. Presentation layout was controlled as a between-subjects variable; each participant memorized an information sequence displayed in either a spatial or a non-spatial presentation layout on the screens of the CAVE. In the non-spatial presentation condition, each card was displayed in the same location on the front wall, directly in front of the participant (this corresponds to the number four position in Figure 7). The spatial presentation condition showed the cards across the left, front, and right walls surrounding the participant. For this condition, the first card started on the left projection wall, with subsequent cards wrapping around to the front and right walls (see Figure 7). Recall that only one card was visible at a time in both conditions.

We tested the effects of landmarks by varying the background on which the cards were projected. The landmark environment condition contained a semicircle of pillars on a checkered ground plane (see Figure 8). This environment was displayed over the three walls and the floor of the CAVE so that the participant was surrounded by the pillars. The complementary condition displayed an empty environment, in which the pillars and ground plane were not shown. Environment background was a between-subjects condition, so that each participant viewed all trials with either the landmark background or the empty background.

We controlled FOV using a within subjects design so that each participant completed two trials with low FOV and two with high FOV (in randomly determined combinations). We considered performance differences when participants had a full, uninhibited FOV compared to trials which limited FOV to 60 degrees of horizontal viewing range. For the low FOV conditions, participants wore goggles that served as physical blinders to limit FOV. For the high FOV conditions, participants wore clear lab goggles having no or negligible effect on FOV. Figure 9 shows the glasses used for the experiment.

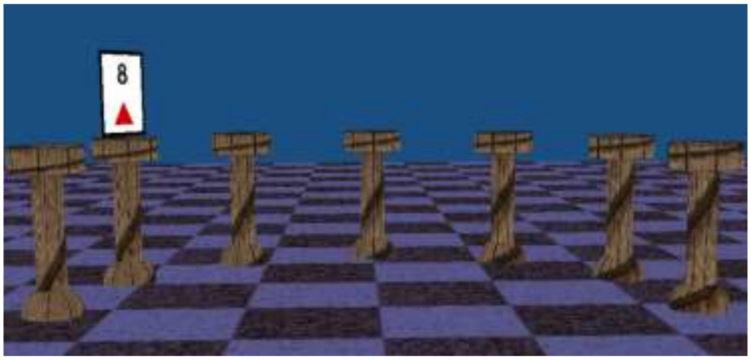


Figure 8. In the landmark environment, the cards appeared on top of pillars in a checkered environment.

Figure 9. The glasses on the left limited FOV to 60 degrees, while the control glasses on the right did not reduce FOV.

4.2.5 Procedure

Before completing any trials, participants were introduced to the CAVE system. Participants then completed a cube comparison test of spatial ability from the Kit of Factor-Referenced Cognitive Tests (1976 Edition) so that we could later test for any correlations of performance to spatial aptitude.

Each trial consisted of viewing the entire card sequence twice and then verbally reporting the remembered sequence outside the CAVE. Each participant first completed a practice trial with five cards. In order to account for issues with color blindness participants, were then tested on the ability to distinguish between the colors used in the cards. Participants then completed four trials (two trials with each FOV) with sequences of seven cards. Because presentation layout was varied between subjects, each participant viewed all sequences (including the practice trial) either with the spatial wrap presentation or with the non-spatial, straight-ahead presentation. Participants were encouraged to rest and relax between trials and were required to take a break for at least three minutes after the first two trials in an effort to reduce any effects of mental fatigue or interference among the different sequences.

After completing the trials, we interviewed participants about the strategies used in performing the experimental task.

Study approval documents and questionnaires for Experiment I are included in appendix A.

4.2.6 Participants

Thirty-two university students and staff members participated in the study. An equal number of male and female participants volunteered and gender was balanced across conditions. Participant ages ranged from 18 to 57 with a median age of 20. We distributed participants across conditions by age as well as possible to limit potential confounding effects of age.

4.2.7 Results and Discussion

We analyzed the effects of presentation layout, FOV, and background environment on task performance outcomes and strategies employed. Additionally, we tested for correlations with spatial ability.

i Performance Outcomes

To analyze the effects of our independent variables on scores and times, we performed a mixed-design ANOVA with FOV as the within-subject factor and considered presentation layout and presence of background landmarks as between-subjects variables. There was a significant main effect of presentation layout on scores with $F(1, 28) = 4.43$, $p < 0.05$. A comparison of these means can be seen in Figure 10. As hypothesized, scores with the spatial presentation (M = 14.50, SD = 2.18) were significantly better than scores with the non-spatial presentation (M = 12.21, SD = 4.16). Figure 10 shows means and standard errors of the means for conditions. Estimates for effect sizes and test power are presented in Table 3. No significant effect of presentation was found for time, $F(1, 28) = 0.30$, with M = 57.45 and SD = 22.86 for spatial and M = 54.13 and SD = 18.65 for non-spatial presentations.

No significant differences in times or scores were found for FOV, with $F(1, 28) = 2.09$ for score and $F(1, 28) = 0.48$ for time. There were also no significant interactions between FOV and presentation layout, with $F(1, 28) = 0.28$ for score and $F(1, 28) = 2.67$ for time. We reject our hypothesis that an increased FOV improves performance for a spatial presentation.

While we expected that participants would be able to use a background environment and its landmarks to aid memory, the presence of such a background had no significant effect on performance, with $F(1, 28) = 0.40$ for score and $F(1, 28) = 0.20$ for time. Several participants even commented that they found the background environment to be distracting and made it difficult to record mental visualizations of the cards themselves. A similar effect was observed in a memory-of-location experiment by Jones and Dumais (Jones & Dumais, 1986), in which it was noted that landmarks may have only cluttered the reference space.

Because there were no significant interactions between the presence of landmarks and presentation style, with $F(1, 28) = 2.22$ for scores and $F(1, 28) = 0.07$ for time, we reject our hypothesis that presence of landmarks improves performance for spatial presentations.

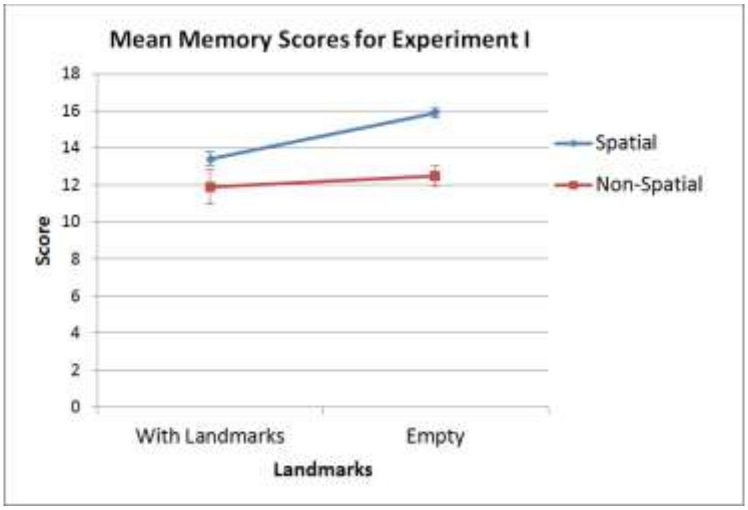


Figure 10. Means for memory scores from Experiment I with error bars for standard error of the mean. Scores were significantly higher with the spatial presentation style.

Variable	F	p	Cohen's d	η_p^2	Power
Presentation	4.426	0.045	0.659	0.136	0.528
Landmarks	1.690	0.204	0.353	0.057	0.241
FOV	2.122	0.156	0.237	0.070	0.291

Table 3. Additional test details for variable effects on memory scores for Experiment I. Effect sizes and power were calculated using alpha = 0.05.

ii Spatial Ability

We also conducted a two-tailed Spearman correlation test of the recall accuracy scores with the scores from the cube comparison test of spatial ability for both the spatial and non-spatial presentation methods. For participants with the non-spatial presentation, we found a significant correlation between spatial ability scores and recall scores, with $\rho = 0.54$ and $p < 0.0001$. No significant correlation was found between recall scores and spatial ability scores for the spatial presentation conditions ($\rho = 0.14$ and $p = 0.26$). These correlations suggest that individuals with higher spatial aptitudes had some advantage in the memorization task with the non-spatial display; however, this advantage was eliminated with the spatial presentation. Additional spatial cues enabled participants to compensate for lower spatial cognitive abilities (similar results have also been observed in previous studies, e.g., (J. Quarles, S. Lampotang, I. Fischler, P. Fishwick, & B. Lok, 2008). Combining this analysis with the significant score improvements gained with the spatial presentation, it suggests that the spatial presentation supported performance improvements regardless of individual spatial aptitude.

We also calculated point-biserial correlations of scores and times with gender for both spatial and non-spatial conditions, finding no significant correlations.

iii Memorization and Recall Strategies

Based on the post-test interview responses, we conclude that the additional spatial cues provided in the spatial presentation did not cause participants to completely change their memorization strategies; rather, it seems that participants used the additional spatial information to supplement other strategies. Participants used whatever strategies were most natural to them (e.g., mental visualization snapshots, repetition, or the creation of patterns) with the mapping of pieces of information to locations in space helping to reinforce these strategies. We analyzed the responses from our interviews in order to categorize the general types of strategies used for the memorization task.

Participants reported using multiple types of strategies or relying on different types of memory cues simultaneously to aid memorization and recall. The most commonly reported strategies included visualizing the cards and/or their locations on the screens, verbally repeating pieces of information, and finding patterns or relationships among the numbers, shapes, or colors of multiple cards. Other reported strategies included associating card information with other familiar, real-world objects (reported by eight participants) and using physical motions or gestures as memory aids (reported by three participants). Focusing on the most commonly reported strategy categories, provides breakdowns of reported strategies for the spatial and non-spatial conditions, as well as for the landmark and no-landmark conditions. Most notably, these tallies show that a visualization strategy was most often employed when a spatial presentation was used. Figure 11 shows a graphical comparison of the common strategies used for the two presentation styles.

We tested for effects of landmarks and presentation style on visualization strategy with a three-way loglinear analysis, which produced a final model that retained all effects. The likelihood ratio of this model was $\chi^2(0) = 0$ and $p = 1$. This indicated that the highest-order interaction (between presentation, landmarks, and visualization strategy) was significant, with $\chi^2(1) = 13.46$ and $p < 0.001$.

Strategy	Total	Spatial		Landmarks	
		Yes	No	Yes	No
Visualization	19	14	5	9	10
Repetition	19	8	11	8	11
Patterns/Relationships	17	10	7	7	10

Table 4. Common strategies used by the participants for the memorization task in Experiment I, broken down by the variables for presentation type and presence of landmarks. Most participants reported using multiple strategies.

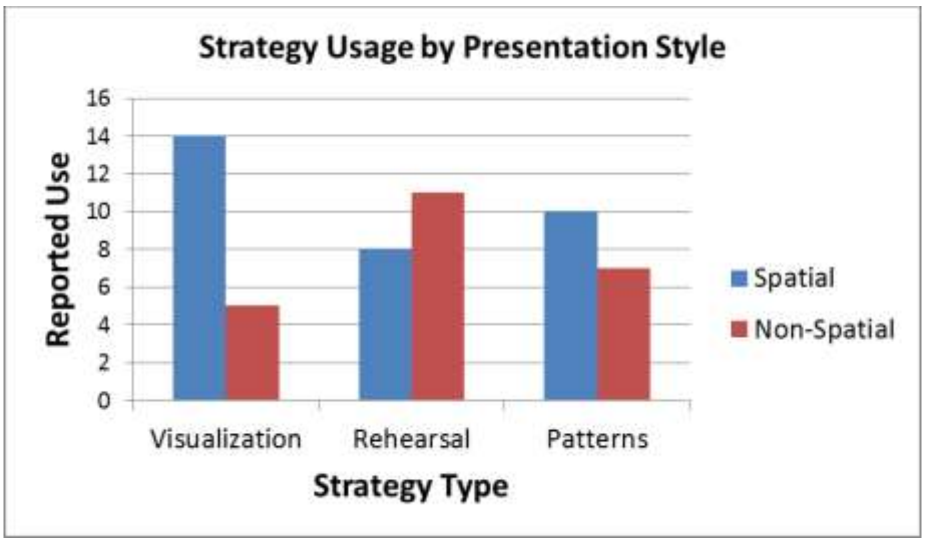


Figure 11. Common participant strategies by presentation style. Significantly more participants used visualization strategies with spatial presentations.

By looking at Figure 11, it is apparent that, overall, participants used visualization strategies more with spatial presentations than with non-spatial presentations. The real difference, however, was between spatial and non-spatial presentations with landmarks present. With landmarks present, all participants employed visualization strategies in the spatial presentation conditions, but participants never employed visualization strategies with the non-spatial presentation (see Figure 12). With landmarks present, odds ratios indicated that participants were 289 times more likely to use visualization strategies with spatial presentations than with non-spatial presentations, as compared with empty VEs without landmarks, for which odds ratio indicated that participants were no more likely (a ratio of 1.0) to use visualization strategies with spatial presentations than with non-spatial presentations.

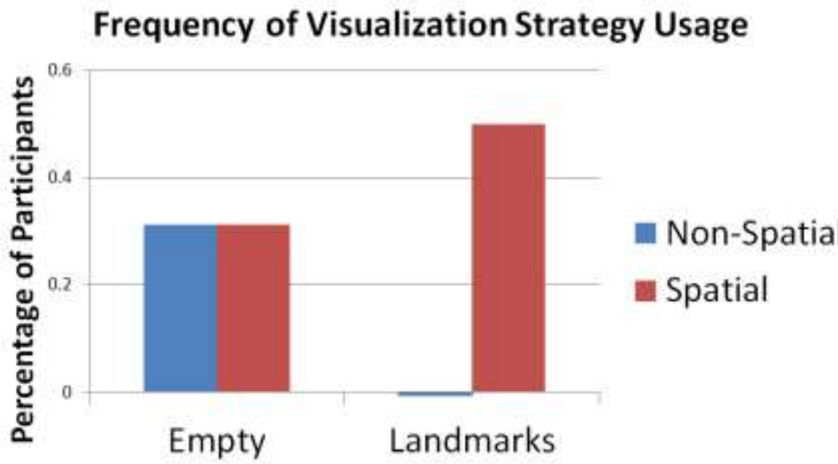


Figure 12. Breakdown of visualization strategy usage by presentation and landmarks. There was a significant interaction between landmarks and presentation style of conditions on the use of visualization learning strategies. With landmarks present, all participants employed visualization strategies in the spatial presentation conditions, but participants never employed visualization strategies with the non-spatial presentation.

4.2.8 Discussion

The results of Experiment I support the hypothesis that a spatial information presentation can improve memorization performance for accuracy (but not recall time). This supports the explanation for the results of our previous study (D. A. Bowman et al., 2009), in which we suspected that increased visual fidelity of a virtual environment caused significant performance improvements for a memorization activity due to the enhanced spatial cues. Based on the results of our post-test interviews, we hypothesize that the additional spatial cues provided in the spatial presentation did not cause participants to completely change their memorization strategies; rather, it seems that participants used the additional spatial information to supplement other strategies. Participants used whatever strategies were most natural to them (e.g., mental visualization snapshots, repetition, or the creation of patterns) with the mapping of pieces of information to locations in space helping to reinforce these strategies.

Based on the combined results of Experiment I and (D. A. Bowman et al., 2009), we hypothesize that increasing spatial cues with spatial organization or enhanced visual stimuli could improve the effectiveness of at least some learning-based applications. The impact of such enhancements, however, depends on the task and learning environment. For example, FOV had no effect on performance in Experiment I, while an increased FOV improved performance on the procedure memorization task of our earlier study (D. A. Bowman et al., 2009).

4.3 Experiment II: Supporting Problem Solving with Spatial Information Presentations

Focusing on the presentation methods, the results of Experiment I show that spatial presentations can not only affect performance in cognitive tasks, but also the strategies used to complete the tasks. Because these effects were observed for a specific and relatively simplistic type of memorization task, we decided to perform a follow up experiment with a more complex problem-solving task.

4.3.1 Introduction

Because knowledge and recollection of facts form a foundational stage of the learning process (Bloom et al., 1956; Krathwohl, 2002) , the results of Experiment I support the idea that the added benefits of a spatial display could hold for learning activities, providing a strong foundation for studying learning in VEs. Experiment I showed that participants performed better with the spatial presentation method, supporting our hypothesis that spatial techniques can be used to support more efficient memorization of procedures; however, it is still unknown whether or not the advantages of a spatial display layout extend beyond simple memorization tasks.

In our second experiment, we moved our investigation beyond memorization, studying the effects of spatial presentation for a cognitive processing task that requires the application of the learned information to solving a problem. This higher level of cognitive processing can be viewed as a more representative example of the type of processing exercised in an educational VE.

4.3.2 Hypotheses

As in Experiment I, we tested spatial and non-spatial information presentations. We hypothesized that participants would be better able to organize and remember images with the spatial presentation, thus improving performance.

In addition to task performance, we also considered strain on working memory, which can affect the ability to process information (Sweller, Merrienboer, & Paas, 1998). Similar to the idea of using external representations to offload mental processing into the world (Norman, 1991), we hypothesized that locations could be used offload organizational processing and memory. Thus, we predicted that participants would experience lower mental workload with a spatial layout than with the non-spatial representation.

4.3.3 Task

Rather than simply allowing participants to complete a task by memorizing the presented information, as in Experiment I, Experiment II required participants to discover new information and use it to solve problems. Similar to Experiment I, the purpose of this experiment was to investigate whether spatial presentation affected performance for a task that did not inherently lend itself to benefits from a spatial distribution. To this end, we created a puzzle task that could be presented on cards in either a spatial or non-spatial presentation. The task involved coordinating information from multiple items and required participants to refer back to previously viewed items to make sense of later items. Participants had to use relationships among separate items to deduce new informational rules, which then had to be applied to different situations in the assessment.

To help explain the cards and task, Figure 13 shows a sample set of five cards. Each card is divided into a left area and a right area. The left area contains zero, one, or two squares with symbols or patterns. The right area contains a gray circle on a vertical scale. The vertical position of the circle is determined by what symbol blocks are included on the left. Different symbol blocks correspond to different positive or negative values that will cause the circle to appear in a higher or lower position on the card. The goal of the task is to figure out the effect of each symbol block on the vertical position of the circle.

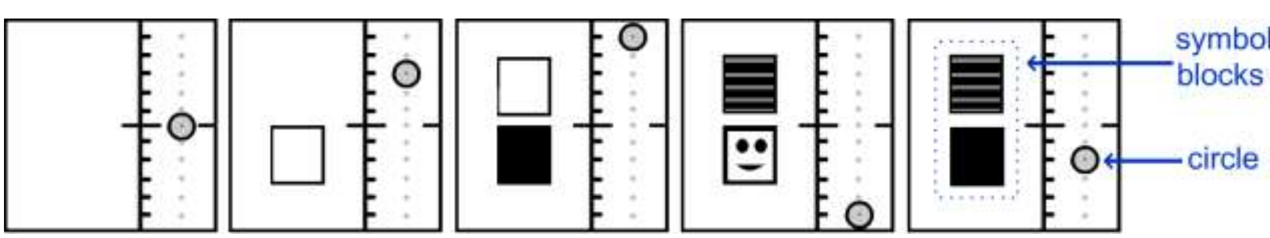


Figure 13. Examples of cards as presented in Experiment 2. In each card, the position of the circle is determined by what symbol blocks are present in the left area.

For instance, Figure 13 shows a sample set of cards as they might be presented in order, one at a time, starting from the left. The leftmost card shows that the circle is in the middle of the scale when no symbol block is present. In the second card from the left in Figure 13, the circle is in a higher position on the card because of the inclusion of the white symbol block. Specifically, the position increases by three ticks on the vertical scale, so the corresponding value is +3. On the third card, the circle is even higher with both a white block and a black block. Because we know the effect of the white block alone, it is possible to figure out the effect of the black block (the black block also corresponds to higher placement, changing the circle's position by +2). The fourth card from the left shows two new blocks: a striped block and a smiley face block. We can see that these cards cause the circle to have a low position on the card, but we cannot determine the exact magnitude of the corresponding values for either block. The fifth card shows the effect of a striped block and a black block together. If we remember the effect of black block, it is now possible to determine the effect of the striped block. In this case, because the black block causes the circle's position to move +2 units, we can figure out that the striped block causes the circle to move -4 movements, explaining why the circle is at the -2 position on the fifth card. By similar logic, if we also remember the previous card with a striped block and a smiley face block, it is now possible to figure out the effect of the smiley face block (-1).

Each trial contained seven cards with different symbols or patterns used for the blocks in each set. That is, no symbol block was reused in multiple sequences. Every card set contained six unique symbol blocks (see Figure 14). Of the seven cards in every sequence, two cards contained only one symbol block and four cards contained two blocks. The first card in every sequence was always the card with no symbol blocks and the circle in the middle of the card (the leftmost card of Figure 13).

Before participants started the trials, the card set shown in Figure 13 was used to explain the cards and how to use the information from multiple cards to figure out the effects of all of the symbol blocks. For this familiarization task, participants were not explicitly told that blocks corresponded to numeric values and a script was used to prevent any hints from being provided in the explanation.

The task was designed to study the effects of a spatial information presentation on a task involving higher levels of cognitive processing than those tested in Experiment I. The task required critical thinking in order to figure out the relationships between individual symbol blocks and their effects on the position of the circle. Participants had to remember pieces of the presented information and relate their meanings to other presented information. They then had to use these relationships to deduce new informational rules, which they had to apply to different situations in the assessment.

Immediately after viewing a sequence of cards twice, participants were tested on their understanding of the effects of the symbol blocks. For this evaluation, participants were presented with cards similar to the previously viewed cards. The evaluation cards, however, did not already have a circle in place on the scale. Participants used a graphical computer application to place the circle in the appropriate position for each card, using a standard optical mouse to click the intended positions. This evaluation was performed for two sets of six cards. In the first set of cards, each card contained a single, unique symbol block. This set of cards tested the ability to figure out the individual effects of the symbol blocks. Cards in the second set contained pairs of blocks, with five of the six cards showing combinations not shown in the previously viewed sequence. This set of cards tested the ability to apply the learned block effects to solve new problems.

Performance was scored based on timing the evaluation and summing errors. Completion time measured the amount of time it took to place all the circles in each card set and then click the “done” button. The error for each card was calculated by taking the difference in magnitude between the correct circle position and the guessed position, with each unit on the scale having a value of one.

We asked participants to rate mental workload using the NASA TLX scale (Hart & Staveland, 1988), a standardized test for measuring perceived workload. Participants used the software version of the TLX assessment. Both the circle placement evaluation and the TLX workload evaluation were completed at a desk next to, but not facing, the CAVE.

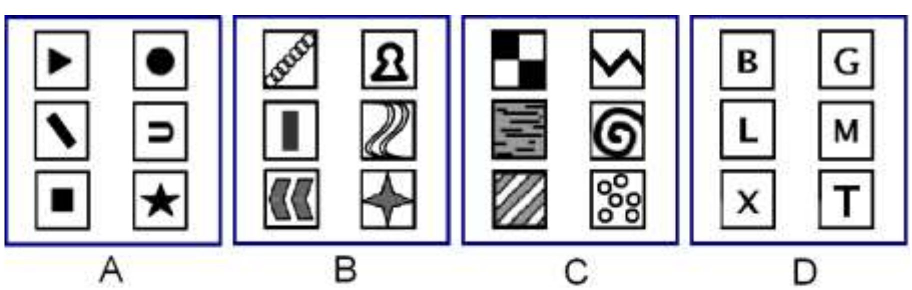


Figure 14. Symbol blocks used in the four card sets of Experiment II. Each card set was composed of one card with no symbol block, two cards with only one symbol block in each, and four cards with two symbol blocks in each.

4.3.4 Card Set Validity Test

We conducted preliminary testing with different card orders and various types of symbols and patterns in order to develop four card sequences believed to be of approximately equal difficulty. We then conducted a validity test of the four sequences to assess any differences in perceived difficulty. For this test, five participants viewed the sequences and completed a circle placement evaluation for a set of six cards, each with a single symbol block. Upon completion of each evaluation, participants were asked to rate the task difficulty on a scale of one to ten, with a rating of ten indicating a very difficult or challenging activity. The results (summarized in Table 5) revealed that the largest difference in mean ratings between any two card sets was 0.8. While participants felt that certain card sets were more or less difficult than others, these differences were not consistent for any particular set. We felt that the results did not show any clear differences in difficulty. Responses in post-test interviews indicate that the differences in difficulties among sets were primarily attributed to individual preferences of the block symbols used. Based on these results, the four sets were considered to be at an approximately equal level of difficulty.

	Mean	**Range**	**SD**
Set A	6.80	5	1.92
Set B	7.60	6	2.19
Set C	7.40	2	0.89
Set D	7.20	4	1.64

Table 5. Perceived levels of difficulty of the four card sets used for the trials based on validity pre-testing

4.3.5 Experimental Design

Four unique card sequences were used for the trials. The orderings were balanced using a Latin square design. The spatial and non-spatial presentation conditions were controlled within subjects, alternated between trials. Because the Latin square for card sets yielded four possible orderings that could be done in two ways due to alternating presentation methods, eight distinct orderings were possible from the 2x4 design.

4.3.6 Participants

Twenty-four university students participated in this experiment (ten were female and balanced across conditions as well as possible). In order to decrease variability of performance differences for our problem-solving task, participation was limited to engineering students between the ages of 18 and 22.

4.3.7 Procedure

Before beginning, participants first completed a brief questionnaire providing simple background and demographic information. Participants were then walked through the familiarization task using paper cards with the card set shown in Figure 13 (as explained in the Task section). The experimenter read the explanation from a script, asked participants if they understood, and reread sections of the script to help clarify any misinterpretations. Participants were then introduced to the CAVE and the familiarization sequence was displayed according to both the spatial and non-spatial methods (order of these presentations was randomized for this familiarization). Participants were then trained in the use of the card evaluation tool. Finally, the experimenter explained the dimensions of the NASA TLX and trained participants on the use of the workload-rating application.

Participants then completed four trials. For each trial, participants were first shown the set of all possible symbol blocks that would be used in the sequence. The sequence of seven cards was presented twice, with each card displayed for six seconds.

After viewing the sequence in the CAVE, participants immediately walked over to a nearby desk to complete the evaluation tasks. Participants first completed the circle placement evaluation for six cards, each with a single symbol block. Next participants completed the same task for six more cards with two symbol blocks each. Participants then provided workload ratings for the NASA TLX workload evaluation.

The experimenter encouraged participants to rest and take breaks between trials to reduce any effects of fatigue. Participants were required to take a brief two- to three-minute break after completing the first two trials. After completing the four trials and their evaluations, participants completed the dimension comparison task for collecting the NASA TLX dimension weights. Lastly, participants completed an exit interview about strategies used, opinions of task difficulties, and differences between conditions and card sets.

Study approval documents and questionnaires for Experiment II are included in appendix B.

4.3.8 Results and Discussion

We did not find a significant difference between spatial (M = 9.39, SD = 6.93) and non-spatial (M = 8.31, SD = 5.82) presentations for single block errors, with $F(1, 88) = 0.75$. We found a significant main effect of card set for the single block errors, $F(3, 88) = 4.25$, $p < 0.05$. A post-hoc, Bonferroni-corrected Tukey HSD analysis revealed that card set D (M = 12.33, SD = 7.04) was significantly different from card set B (M = 6.29, SD = 5.43) at the $p = 0.05$ level, with d = 0.97.

No significant difference was found between spatial (M = 14.81, SD = 6.97) and non-spatial (M = 13.69, SD = 8.27) presentations for double block errors, with $F(1, 88) = 0.64$. There was a significant main effect of card set for errors of the double block assessment with $F(3, 88) = 9.04$ and $p < 0.0001$. A post-hoc, Bonferroni-corrected Tukey HSD analyses at the $p = 0.05$ level showed card set D (M = 19.71, SD = 7.46) was significantly different from set B (M = 10.50, SD = 6.53), with d = 1.32, and that set D was also significantly different from and set C (M = 11.38, SD = 6.72), with d = 1.17.

No significant main effects due to presentation, with $F(1, 88) = 0.01$, or card set, with $F(3, 88) = 1.29$, were found in completion times for single-block assessments. Similarly, no significant main effects due to presentation, with $F(1, 88) = 0.25$, or card set, with $F(3, 88) = 0.55$, were found in completion times for double-block assessments, and no significant differences in overall mental workload were found due to either presentation, with $F(1, 88) = 0.37$, or card set, with $F(3, 88) = 1.96$.

We also conducted separate repeated-measures one-way ANOVA tests on the effects of presentation mode on each of the workload dimensions from the NASA TLX. We found no significant effects for mental demand ($F(1, 23) = 0.396$), physical demand (all participants reported zero ratings for this dimension), temporal demand ($F(1, 23) = 0.074$), performance ($F(1, 23) = 0.003$), or frustration ($F(1, 23) = 0.005$). There was a significant main effect of presentation on the effort dimension, with $F(1, 23) = 5.097$, $p = 0.034$, and Cohen's d = 0.224. The spatial presentation did have significantly lower mental workload scores for effort, with M = 158.875 and SD = 81.395, as compared to the non-spatial presentation, with M = 177.354 and SD = 83.646. Noting the small effect size of d = 0.224, this provides little evidence towards our hypothesis that the spatial presentation would have reduced mental workload over the straight-ahead presentation mode.

Because we found no differences in overall mental workload, times, or errors between the spatial and non-spatial conditions, we reject the hypotheses that the spatial information presentation supports improved performance and lower workload for the task. We found no significant interactions between presentation and card set for any of the metrics. We also tested for order effects using a one-way, non-parametric ANOVA (Wilcoxon signed-rank test) at $p < 0.05$. No significant order effects were found for any of the metrics.

Additionally, despite our efforts to develop card sets of equal difficulty, the significant differences between card sets indicate that this was not the case. In general, the time and error results show that card set D was harder than sets B and C. It is believed that these differences are primarily the result of differences in the ordering of cards with single and double blocks in the presentation sequences. As an example, refer to the sample sequence of Figure 13. It is easy to imagine how the task would be much more difficult if the second card of Figure 13 was presented at the fourth or fifth position in the sequence, rather than at the second position.

Another possibility is that participants were better able to remember and associate the symbol blocks of different sets. The blocks of set D, for example, simply used alphabetic letters instead of shapes or patterns (see Figure 14). While it is possible that performance results were worse for set D due to difficulties working with letters, based on a comparison of the sequences, we think that it is more likely that the differences can be attributed to the ordering of cards using single and double symbol blocks within the sequences. Interestingly, while performance results for set D were significantly different than B and C, opinions about the difficulty levels for the card sets generally balanced based on the exit interviews. For example, of the 24 participants, seven reported that the sequence using set D was the easiest of the four sets, while seven felt it was the hardest.

4.4 General Discussion of Experiments I and II

While Experiment I revealed that recall accuracy was higher with a spatial information presentation within a VE, the results of Experiment II do not support the hypothesis that the benefits extend to more complicated learning activities. The task was designed to encourage a problem-solving approach during the information presentation phase. Rather than have participants simply memorize the presented information and then use that information to solve problems, the task required critical thinking in order to deduce the relationships between individual blocks and their effects on the position of the circle. Responses in our exit interviews confirm that this was the approach that all participants employed. It is possible that, although a spatial layout aids performance for simple memorization, no advantage is gained for this type of critical thinking activity.

Another possible explanation is that practice and repetition are needed to learn how to take advantage of additional spatial cues for improved performance. The memorization study of Experiment I provided participants with a practice trial and followed a between subjects design. Thus, participants completed all trials under the same presentation condition. It could be that practice and presentation consistency are necessary in order to develop a successful strategy for taking advantage of the spatial presentation.

Another issue for consideration is the visuospatial nature of the problem-solving task in Experiment II. It has been theorized that humans possess two types of working memory: visuospatial and phonological (Baddeley, 1998). The visuospatial memory store is used for images and spatial information. Because the block and circle task involved a high amount of image processing and analysis of spatial relationships, it could have overloaded the visuospatial memory store. The overloaded spatial memory would then be unable to take advantage of the additional organization support offered by the spatial presentation. Past work by Wickens and Liu (C. D. Wickens & Liu, 1988) suggests that information processing tasks can work in cooperation with each other if they use different memory stores. In contrast to the problem solving activity, participants could rely heavily on the phonological type of memory in the memorization task of the previous experiment. Thus, the memorization task may have left significantly more visuospatial memory available to take advantage of the spatial organization of the wrap-around presentation method. Based on the participants' descriptions of their strategies, we know that many used verbal encodings to remember the symbol blocks; however, we were unable to determine what mental processes or memory types participants were using to organize and relate the pieces of information. A similar study using a simpler critical-thinking task that is more verbal in nature could be used to further investigate this explanation.

An alternative explanation is the need for spatial location to serve as redundant coding of information in order to provide any performance benefits. Past research (e.g., C. D. Wickens, Goh, Helleberg, Horrey, & Talleur, 2003) has shown benefits of redundant combinations of data presentations. In Experiment I, as well as in other past studies finding benefits to spatial presentation (Hess et al., 1999), spatial position was coupled with other information to aid memory. In the problem-solving task of Experiment II, however, spatial locations were arbitrary and meaningless. It may be worth investigating whether coding redundancy is necessary for performance gains for memorization tasks, and if spatial presentation offers benefits for problem solving activities when location adds informational redundancy.

Our interviews revealed that participants were attempting to deduce either the approximate effects or the exact associated values of the symbol blocks in Experiment II; however, because the symbol blocks could appear in multiple cards, we think that participants were not mapping these effects and values to locations in space. The information that participants were struggling to remember had to be deduced during the trials, and so it was not clearly presented in a spatial layout. As a result, the spatial positions had little meaning in the task. This is clearly in contrast with Experiment I, in which the information that participants were trying to remember was clearly mapped to separate locations in the spatial presentations. In problem solving activities or other tasks in which users must create new information based on existing material, we hypothesize that interactive methods may allow users to give their own meaning to locations. We suspect that educational VE applications could support the creation of meaningful informational mappings to locations through organizational interactions, annotations, or navigational control.

4.5 Conclusions of Experiments I and II

With Experiments I and II, we studied if and how users take advantage of spatial mappings in learning tasks. These studies have shown that learners do employ a variety of strategies involving the spatial layout of information. While the results of Experiment I and previous studies (Hess et al., 1999) indicate that spatial presentations of information support performance advantages for memorization tasks, spatial layouts afforded no such advantages over non-spatial presentations for the problem-solving task of Experiment II. Spatial information presentation alone may not be enough to support performance improvements for every task. Our next experiments further explore factors influencing the effective use of space.

5 Experiment III: How Spatial Layout, Interactivity, and Persistent Visibility Affect Learning

5.1 Summary

Experiment III explores how spatial layout complexity and view control impact learning and investigates the role of persistent visibility when working with large displays. This work (Ragan, Endert, Bowman, & Quek, 2012) was published in Proceedings of the 2012 International Working Conference on Advanced Visual Interfaces (AVI 2012). We performed a controlled experiment with a learning activity involving memory and comprehension of a visually represented story. We compared performance between a slideshow-type presentation on a single monitor (i.e., low layout complexity) and a spatially distributed presentation among multiple monitors (i.e., higher layout complexity). We also varied the method of view control (automatic vs. interactive). Additionally, to separate effects due to location or persistent visibility with a distributed layout, we controlled whether all story images could always be seen or if only one image could be viewed at a time. With the distributed layouts, participants maintained better memory of the associated locations where information was presented. However, learning scores were significantly better for the slideshow presentation than for the distributed layout when only one image could be viewed at a time.

5.2 Goals

Our first two experiments provided evidence that learners do modify their learning strategies to take advantage of a spatial presentation. Further, the results suggest that spatial information presentations can improve learning effectiveness when the information of primary interest is mapped to locations. But additional data was needed to generate design recommendations for spatial presentations. In Experiment III, we studies differences in presentation effectiveness due to varying layout complexity, as the spatial presentations of Experiments I and II only had low layout complexities. As our first two experiments employed fully automated presentations, the following experiment also considers how interactive view control affects learning effectiveness and the use of strategies.

Experiment III uses 2D graphics, as is common for many visualization applications that support information processing with spatial presentations. For example, intelligence analysis tools help analysts to make sense of large information sets by looking through clustered documents (Wise et al., 1995). As an example in a school setting, a student can use a linear strip of thumbnail previews to help keep track of the PowerPoint slides while studying. For applications that hope to preserve the spatial mapping between virtual and physical locations, the possibilities for spatial layouts are limited the available display space. As such, the ability to maintain persistent visibility depends on the available types of computer displays. Smaller displays (such as a single laptop monitor) limit how much information is visible at a time and cannot display full-size items in a spatial presentation. Though costly, larger displays allow for persistent spatial layouts of information to help users visualize relationships among pieces of information. The role of persistence for the use of space is unclear, and it is highly relevant for the use of both large displays and VEs. In this study, we investigate whether alone is sufficient to provide benefits for cognitive processing, or if the notion of persistence is also required for an effective spatial information presentation.

5.3 Part I: Layout Complexity and Interactivity

We conducted a controlled experiment to investigate how learning performance and learner strategies are affected by: (1) the layout complexity of information in a spatial presentation, and (2) interactive control over information viewing.

5.3.1 Hypotheses

Past research has found evidence that users externalize memory and thought into space while using interactive, large-display systems to analyze information (e.g., Andrews, Endert, & North, 2010). We hypothesized that a distributed spatial layout (i.e., higher layout complexity) would support superior learning performance due to the increased variety in available positional cues.

Further, we hypothesized that interactive, user-controlled viewing would improve task performance. We expected that interactive view control would improve learners' abilities to map information to locations in space, enabling the use of spatial indexing as a memory aid. We suspected that the added element of interactivity would allow users to give further meaning to the space, strengthening the effectiveness of the information mapping.

5.3.2 Task

To test our hypotheses, we designed a story task to evaluate both comprehension and detail recall. Participants viewed a set of 25 event cards. The cards included simple, graphical representations of nine visually distinct characters in various situations along with single-word titles to describe the event. Figure 15 shows samples of card images, and the complete set of images is included in appendix C. The cards portrayed simple events with the same characters so that sequences of events could be interpreted as short sub-stories. Additionally, individual characters and events contributed to multiple sub-stories, causing significant overlap among sub-stories and allowing the entire collection of events to be interpreted as a single large, complex story. The primary story sub-plots include: a car accident, a store robbery, shopping, a birthday party, and a broken window. Participants were asked to determine the story and sub-stories based on the events viewed in the cards.

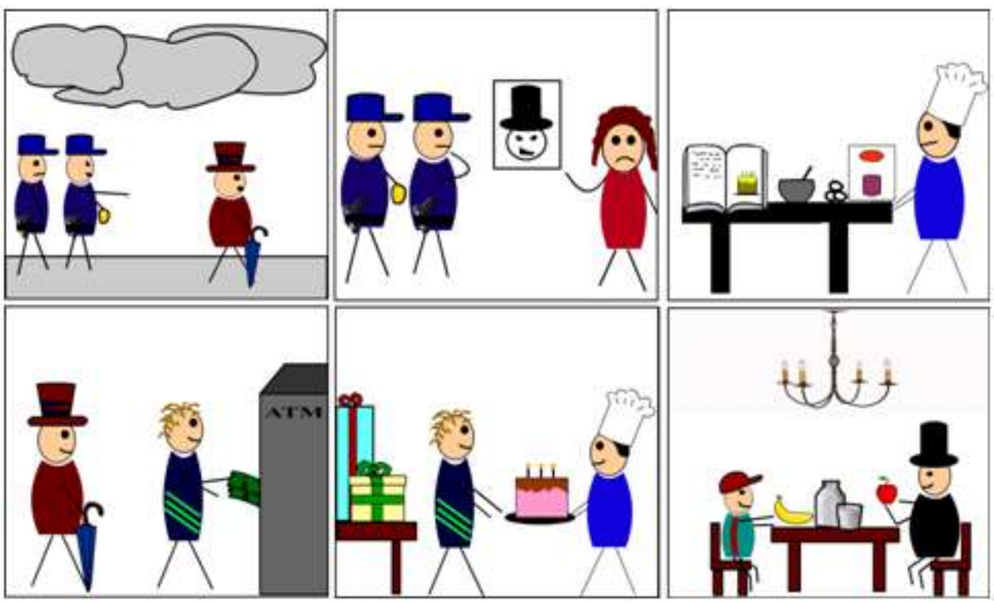


Figure 15. Examples of images used in the dataset. Starting from the upper left corner and moving clockwise, the titles of these cards are: Point, Police, Cook, Eat, Cake, and Bank.

The size of the data set and the complexity of the overlapping sub-stories were determined through a series of small pilot studies. Because this was a controlled experiment and the total viewing time was held constant (as explained further in the *Design* section), images were chosen over purely textual information in order to avoid confounds due to participants' different reading speeds. The data set was designed to support questions of both memory of details and understanding of story events. The question set and scoring criteria focused more on the more significant events for the main story plots (e.g., the robbery or car crash) than on less significant events (e.g., mowing the lawn or walking the dog).

After viewing the event cards, participants were asked a series of questions to test their knowledge and understanding of the presented information. Participants' verbal responses were videotaped in order to aid scoring based on a prepared rubric (included in appendix C). Questions were designed to evaluate comprehension of the meaning of the events and stories as well as simple detail recall. For questions focusing on memory of details, participants earned points for correctly recalling characters and details from the events shown in the story cards. Examples of a detail recall questions include:

- What food products were present in the "Eat" scene?
- What character or characters were in the "Gym" scene?

Other questions evaluated comprehension, involving understanding of the meaning of the events and stories. These questions required participants to do more than simply recall the images on the panels. To earn points for these questions, participants were required to explain connections among the characters, explain what caused events to occur, or hypothesize future events and appropriate emotional states of the characters. Examples of comprehension questions are:

- Can you come up with a sub-story of events that link the boy with a red baseball cap to the man with an umbrella?
- How would you expect the man with a black hat to be feeling at the end of the day, and why?
- Describe an event or scene that you would expect the man in the black hat to be doing after the events shown in the story.

Scoring was calculated in accordance with a pre-constructed rubric, with separate scores calculated for detail recall and comprehension questions. The total score was based on all questions.

5.3.3 Design

Participants viewed the event cards on a ten-monitor display, configured in a curved 120° arc with a 2x5 arrangement (see Figure 16). Each monitor was 17 inches with 1280x1024 resolution. Participants sat in a swivel chair in front of the display. Because each participant could only complete the learning task a single time, viewing mode and presentation style were varied in a 2x2 between-subjects design. The two viewing modes we tested were *automatic* and *interactive* control, and the two presentation styles were *slideshow layout* (1D layout complexity) and *distributed layout* (2D layout complexity).

Only one card image was ever visible at a time. In the slideshow layout, all cards were presented in the same location (see Figure 17). The slideshow layout was shown on a single monitor directly in front of the participant (see Figure 18). Below the location where the cards were shown, a horizontal list always showed all textual titles. In the distributed presentation style, the cards were distributed across all monitors of the display so that every card had its own persistent location (see Figure 16). While only a single card image was shown at a time, the locations of all cards were always visible as empty boxes with the textual titles visible. In this way, both presentation conditions always had all titles visible and provided a spatial location corresponding to each image; however, these locations had much higher spatial variance in the distributed layout where the images themselves were displayed in different locations. This allowed us to isolate the effects of spatial location without the confounding effects of persistent visibility that is afforded by normal large-display workspaces. For both presentation styles, the cards were ordered or arranged in the same predetermined organization—events were jumbled so that the stories were not presented in chronological order.

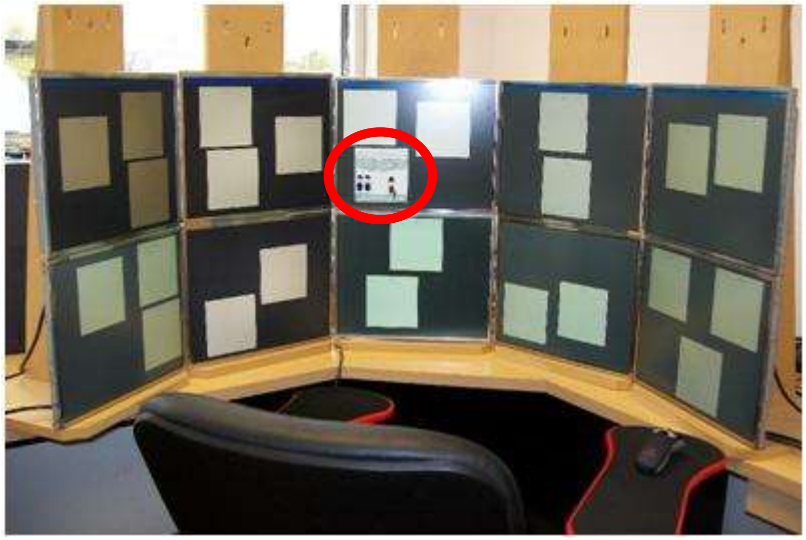


Figure 16. The ten-monitor display to be used for Experiment III. This image shows the story cards distributed in a distributed layout. Note that only one event image is visible at a time (circled in red here).

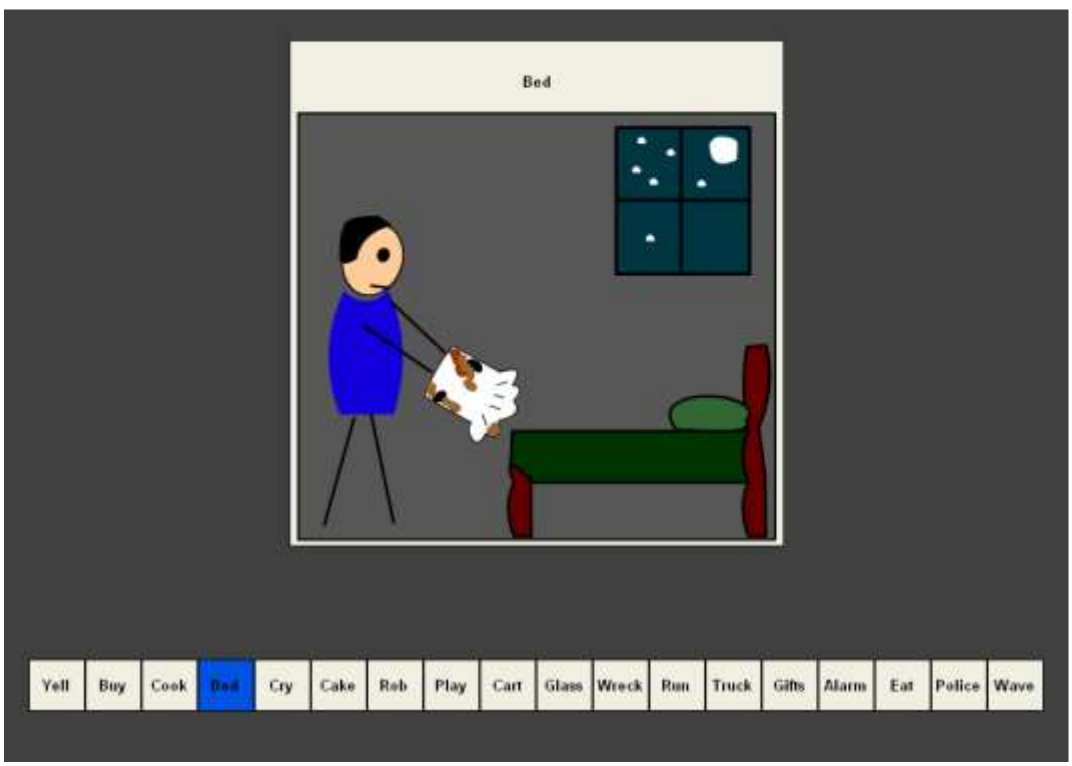


Figure 17. A closer view of the slideshow layout for Experiment III. The *Bed* label is highlighted in the list at the bottom, and the corresponding image is shown.

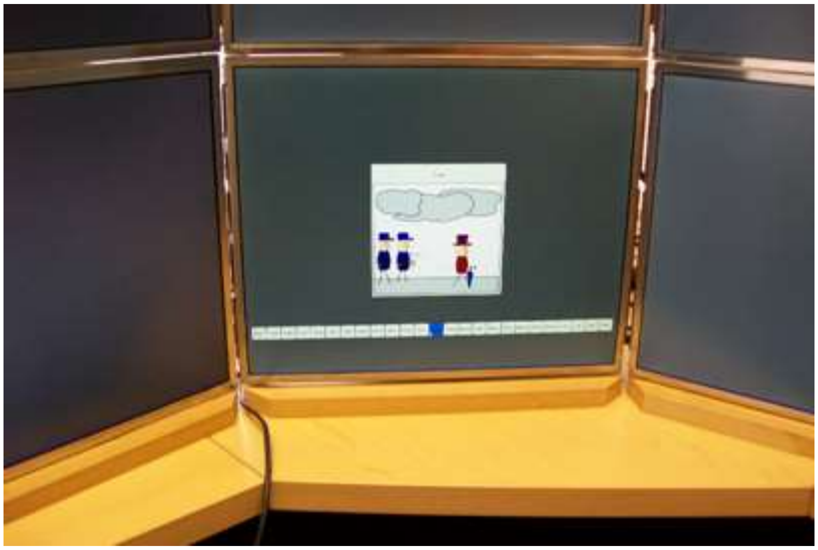


Figure 18. The display for Experiment III with the slideshow layout. All images are viewed at the same location on a single monitor. Below the image location is a list of labels that correspond to the image cards. The label for the currently shown card is blue in the list.

In the automatic presentation conditions, each card image was displayed for five seconds before it was hidden and the next image was displayed. Every card was shown twice in this fashion. In the slideshow condition, all cards showed up at the same location, but card order progressed from left to right through the list of titles. Cards were also displayed from left to right (in the same order) for the distributed conditions. Participants had no way of interacting or controlling the view of the cards.

In the interactive control conditions, each participant used a mouse to manually control the order and duration in which card images were viewed. The participant could make a card image visible by moving the mouse cursor over its title in the slideshow list or over its card in the distributed layout. The total amount of viewing time was limited to 250 seconds—the same as in the automatic conditions.

In all conditions, images and titles were hidden when the viewing period ended, but blank cards or labels remained on the display as placeholders for where the information was displayed. That is, for the distributed layout, blank cards were left on the display for the remainder of the evaluation; for the slide-show layout, empty blocks were still visible in the title list (but with no text).

We studied the effects of viewing mode and presentation style on a variety of metrics. In addition to learning scores, we also asked each participant to report a percentage of confidence of story comprehension. We also measured location recall by having participants point to the blank placeholders and report what event was shown at each location. Video recording and eye tracking were used to aid scoring and to study participant strategies.

5.3.4 Procedure

After having participants complete a general demographic questionnaire, we explained the task and the display system with the aid of a prepared script. Using a small set of event cards with no information relating to the actual story of the primary task, we provided a brief demonstration of how they would be viewing the story images. For participants in the interactive viewing conditions, this included practice using the mouse. We again reviewed the purpose of the task, asking participants to identify the stories and encouraging them to pay attention to how the characters are connected. Participants were informed that the images were jumbled and the image organization was independent of the chronology of the story.

Participants then viewed the cards in the manner determined by their experimental condition. Immediately after the viewing phase, we verbally administered a portion of a number-memorization test to help clear working memory of information about the story set before our real questions. For this test, we verbally listed a sequence of numbers and then asked participants to write down those numbers. This task took approximately one minute, helping to establish that the following questions would be answered based on information from long-term memory (memory research has found that retention in working memory is generally limited to around ten to fifteen seconds without active rehearsal (e.g., J. Brown, 1959)).

We then verbally asked the questions for the evaluation of learning. Next, we asked participants to describe their strategies and thought processes when viewing the information and when answering the questions. Finally, referring to the blank placeholders remaining on the display, we asked participants if they remembered any of the corresponding events for the locations.

Study approval forms, instructions, and assessment materials are included in appendix C.

5.3.5 Participants

Thirty-two undergraduate students participated in Part I of the study. An equal number of male and female students participated, with gender balanced across conditions. Participants came from a variety of academic disciplines, also balanced as well as possible. Ages ranged from 18 to 23 years with a median age of 20 years. Participants came from a variety of academic disciplines.

5.3.6 Results

Because Shapiro-Wilk tests of normality for each of our metrics suggested that they were normally distributed, we were able to use two-way factorial analyses of variance (ANOVA) to analyze the results. We performed multiple analyses to test the effects of presentation style and viewing method on various performance outcomes. The analysis for total learning score showed a significant main effect of presentation layout on overall scores, with $F(1, 28) = 10.21$ and $p < 0.005$. Total scores were significantly better with the slideshow-style presentation ($M = 74.19$, $SD = 19.44$) than with the distributed layout ($M = 51.31$, $SD = 20.00$). The effect size was large, with Cohen's $d = 1.16$. This was the opposite of the hypothesized effect of presentation layout.

The same effect was also found for the ANOVA test for comprehension scores. Comprehension scores were significantly better with the slideshow-style presentation ($M = 50.00$, $SD = 16.31$) than with the distributed layout ($M = 32.63$, $SD = 16.19$), with $F(1, 28) = 9.76$, $p < 0.005$ and $d = 1.07$.

For detail recall, scores were better with the slideshow-style presentation ($M = 24.19$, $SD = 4.32$) than with the distributed layout ($M = 20.56$, $SD = 6.17$), but this was not significant at $p < 0.05$ level. However, with $F(1, 28) = 3.53$ and $p = 0.07$, we suspect that this effect would have been significant with more trials.

No significant effects on learning scores were found due to viewing mode, with $F(1, 28) = 0.04$ for total scores, $F(1, 28) = 0.02$ for comprehension scores, and $F(1, 28) = 0.42$ for detail recall scores. No significant interactions were found between viewing mode and presentation layout for learning scores, with $F(1, 28) = 0.42$ for total scores, $F(1, 28) = 0.10$ for comprehension scores, and $F(1, 28) = 0.21$ for detail recall scores.

An analysis also found a significant effect on location recall (the number of event locations that participants could correctly recall after the questions) due to presentation style, with $F(1, 28) =$

14.70 and $p < 0.001$. This showed that participants were better able to remember the associated locations for events with the distributed layout (M = 9.56, SD = 3.54) than in the slideshow presentation (M = 5.19, SD = 2.93), with a large effect size of Cohen's d = 1.35. Location recall was not significantly affected by viewing mode, with $F(1, 28) = 0.01$, and no interaction was found between presentation style and viewing mode, with $F(1, 28) = 2.35$.

The analysis of confidence of comprehension did not show significant differences due to presentation style, with $F(1, 28) = 3.00$, or viewing mode, with $F(1, 28) = 0.03$. However, the test did show a trend with confidence levels being higher for the slideshow presentation (M = 63.81, SD = 19.32) than the distributed layout (M = 49.44, SD = 25.99), with $p = 0.09$.

5.3.7 Discussion

While we had hypothesized that participants would achieve higher learning scores with the distributed layout, this was clearly not the observed outcome. Learning scores were significantly lower in the distributed layout than in the slideshow-style presentations.

The location recall results indicate that participants were better able to remember the associated locations for event cards with the distributed layout. However, the performance results suggest that these additional location memories did not support performance improvements, despite the fact that many participants were referring to locations to aid recall during questioning (a more detailed presentation of participant strategies is given in Part II).

These were surprising results, as previous research with spatial distribution found the opposite effect (Hess et al., 1999; Ragan, Bowman, et al., 2012), as in Experiment I. But unlike in Experiment I, both presentations in Experiment III did have a spatial distribution (i.e., the list of titles in the slideshow presentation and the card distribution in the distributed layout). So, while unexpected, the results of Experiment III do not contradict those of Experiment I. Additionally, the tasks of the two studies are clearly different, with Experiment I involving memorization of symbols and Experiment III involving story images and understanding. It would be interesting to compare the presentation styles of Experiment III to a completely non-spatial distribution, as done in Experiment I, to learn more about the how the effects of spatial distribution depend on task specifics.

Though our original hypothesis was not supported, we can at least hypothesize other explanations for the better learning scores with the distributed layout. Since no interactions were observed between presentation style and viewing mode, the results of this study suggest that users did not suffer from problems interacting with the mouse in a larger space. We also know that the results were not due to poor spatial memory since participants had better memory of locations in the distributed layout conditions.

One possible explanation is that participants performed better with the slideshow presentation due to higher familiarity with similar presentation styles (e.g., viewing PowerPoint slides, web browsing with multiple tabs, switching among multiple open documents or applications on a single monitor). Alternatively, it could be that it takes practice to establish effective spatial strategies when using larger workspaces; we leave this to future work.

Another explanation—and our current hypothesis—is that perhaps spatial mappings are only useful when the locations carry meaning for the data. That is, the results could be different if the information was spatially grouped with some meaningful organization, such as by chronology or by characters. Because card placements were jumbled in our organizations, locations did not provide additional organizational cues. In future work, we plan to further investigate the relationship between the use of locations and meaningful spatial organization.

As there were no significant differences due to viewing mode, we reject the hypothesis that interactive viewing enables learning improvements. This result has important educational implications, providing evidence that simply adding interactivity does not guarantee learning benefits. Further, because the location recall results showed no effects due to the presence or absence of interactivity, we reject the claim that interactive viewing gives additional meaning to locations or makes information locations easier to remember. It could be that view control is not a complex enough type of interactivity to add meaning to a location. Another possibility is that viewing mode had little effect due to the relatively small size of the data set or the relatively short viewing time.

After Part I of the experiment, it was unclear how learning performances would compare with a standard spatial distribution. As all conditions in the first part of the experiment allowed participants to view only one image at a time, the distributed layout presentations lacked the persistent visibility of information that is normally available with spatial layouts on large-displays. By intentionally crippling persistence in the distributed layouts, we were able to isolate effects due to spatial locations. But how much does persistent visibility really affect the use and benefit of a spatial layout? To address this question, we expanded the experiment by adding an extra condition to help investigate whether learners would take advantage of the distributed layout if all information were visible at all times.

5.4 Part II: Accounting for Persistent Visibility

The first part of the experiment focused on studying learning differences due to varying levels of layout complexity without persistent visibility. In the second part, we extended the experiment to study how persistent visibility affects learning performance and learning strategies. By maintaining the same design and evaluation as used in Part I, we were able to add an additional condition to further our investigation of how learners use spatial presentations to learn and understand new information.

5.4.1 Hypotheses

We hypothesized that a distributed presentation with persistent information visibility would allow learners to use the locations of the spatial layout to help organize information and aid recall. Thus, we expected the addition of persistent visibility to lead to better learning scores than achieved in the distributed presentations from Part I. Also, due to the ability to view and compare multiple images at the same time, we expected performance improvements over the slideshow-style presentations.

5.4.2 Design

For part II of the study, we ran one new condition to compare to the results from Part I. Thus, Part II used the same experimental task, procedure, and evaluation metrics as Part I. Ten undergraduate students (three males and seven females, ages 18 to 21) from various academic disciplines participated in the new condition. Thus, combined with the 32 participants from Part I, the full experiment had a total of 42 participants.

The new condition used a distributed layout with the same organization as the distributed layouts of Part I. However, instead of having only one image visible at a time, as with the automatic and interactive presentations, all card images were always visible for the duration of the viewing phase.

As with the conditions in Part I, a 250 second time limit was enforced. Also as in the previous conditions, the images and titles were hidden when the time limit was reached, leaving only blank cards on the display.

5.4.3 Results

We analyzed the results by considering learning scores, memory of locations, and participant strategies for all conditions from Part I and Part II of the experiment.

5.4.4 Learning Performance

To analyze performance results, we treated each of the four conditions from Part I as a separate group and added the new condition from Part II, giving us five distinct presentation conditions. We again tested each of our metrics for normality with Shapiro-Wilk tests, finding that the learning scores were approximately normally distributed. We tested for differences in learning scores among the five conditions with a one-way independent ANOVA for each score category (total score, comprehension, and detail recall).

The analysis for total scores found a significant main effect due to viewing condition, with $F(4, 37) = 3.54$ and $p < 0.05$. Figure 19 shows means and standard deviations for total scores. A post-hoc Student's t-test revealed that scores for the persistent-visibility distributed condition and both the slideshow conditions were significantly higher than the automatic and interactive distributed conditions (Table 6 shows effect sizes for significant pairwise comparisons). The post-hoc test did not show a significant difference between the automatic and interactive distributed conditions.

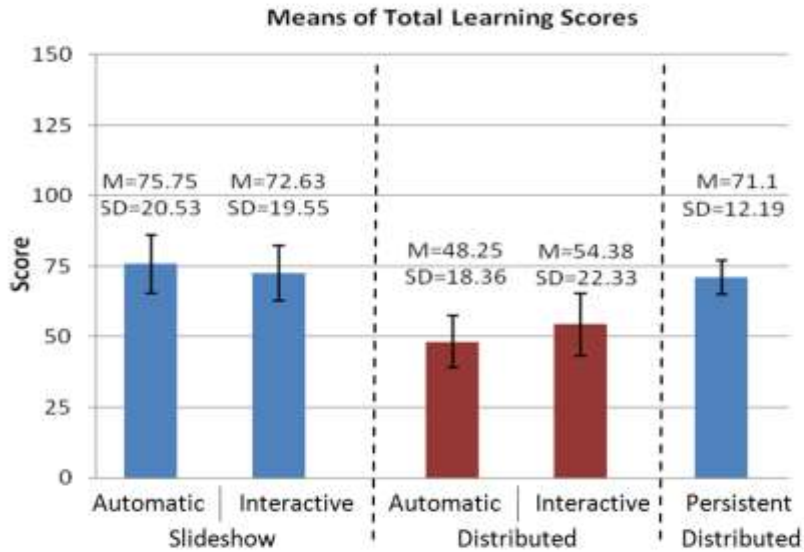


Figure 19. Means of total learning scores with standard deviations after Part II. Different colored bars are significantly different. Scores for the persistent-visibility distributed and both slideshow conditions are significantly better than both the automatic and interactive distributed conditions.

Pair		**Cohen's d**
Persistent distributed	Automatic distributed	1.50
Persistent distributed	Interactive distributed	0.97
Automatic slideshow	Automatic distributed	1.41
Automatic slideshow	Interactive distributed	1.00
Interactive slideshow	Automatic distributed	1.29
Interactive slideshow	Interactive distributed	0.87

Table 6. Effect sizes for significant pairwise comparisons for total learning scores.

The analysis for comprehension scores also revealed a significant main effect with $F(4, 37) = 3.13$ and $p < 0.05$. As with the total scores, a post-hoc Student's t-test showed that scores for the persistent-visibility distributed ($M = 49.10$, $S = 8.94$), the automatic slideshow ($M = 50.50$, $S = 17.11$), and the interactive slideshow ($M = 49.50$, $S = 16.63$) conditions were significantly higher than the automatic ($M = 31.25$, $S = 17.40$) and interactive ($M = 34.00$, $S = 15.95$) distributed presentation conditions. Table 7 shows effect sizes for significant pairwise comparisons.

Finally, with F(4, 37) = 1.10 and p = 0.37, the analysis for detail recall scores did not show a significant effect.

Pair		Cohen's d
Persistent distributed	Automatic distributed	1.36
Persistent distributed	Interactive distributed	1.21
Automatic slideshow	Automatic distributed	1.12
Automatic slideshow	Interactive distributed	1.00
Interactive slideshow	Automatic distributed	1.07
Interactive slideshow	Interactive distributed	0.95

Table 7. Cohen's d effect sizes for significant pairwise differences between comprehension scores.

5.4.5 Location Recall

Figure 20 shows average location recall scores for all conditions. We tested for differences in location recall among the five conditions with a one-way independent ANOVA. The analysis showed a significant main effect with F(4, 37) = 7.42 and p < 0.0005. A post-hoc Student's t-test showed that location recall for all distributed layouts was significantly higher than the slideshow conditions (Table 8 shows effects sizes for significant pairwise comparisons). Though the persistent-visibility distributed layout did have the highest overall location recall scores, scores were not significantly different among the three distributed layout conditions.

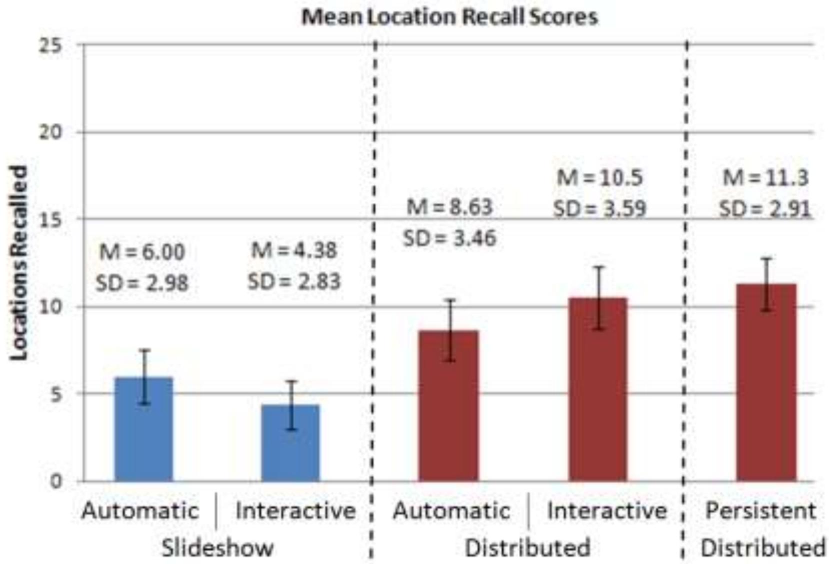


Figure 20. Mean location recall scores. Different colored bars are significantly different. Location recall was higher with all distributed layouts than with the slideshow presentations.

Pair		**Cohen's d**
Persistent distributed	Automatic slideshow	1.80
Persistent distributed	Interactive slideshow	2.41
Automatic distributed	Automatic slideshow	0.82
Automatic distributed	Interactive slideshow	1.35
Interactive distributed	Automatic slideshow	1.37
Interactive distributed	Interactive slideshow	1.91

Table 8. Effect sizes for significant pairwise comparisons between location recall scores.

5.4.6 Learning Strategies

We also studied participant learning strategies by analyzing standard video recordings, eye-tracking video, and interview responses. We considered two general types of strategy classification: *viewing order* and *intentional use of locations*.

For this activity, *viewing order* is the order in which card images were viewed during the learning session. Participants in the automatic presentation conditions were not able to control the viewing order because the images were shown to them automatically. In both interactive conditions and in the persistent-visibility distributed condition, participants were able to choose the viewing order. Most participants (73%) from these conditions employed the same general type of viewing strategy. At the beginning of the viewing session, these participants first briefly scanned over the entire data set in an attempt to get an overview of all cards. They then began to search for and focus on specific images based on logical story constructs (e.g., time of day, same characters). Other participants (23%) did not spend any time scanning the entire dataset, and immediately began trying to search for and match events and characters. One participant from these conditions (specifically, in the interactive distributed layout) never used a search-and-match type viewing strategy, but instead continually scanned over the entire card set for the duration of the viewing time.

We also considered *intentional use of locations* during the task. That is, we studied whether or not participants intentionally attempted to use locations to aid in their learning or recall. This was determined through the post-study interview, in which we asked participants if they tried to use the locations during the learning or questioning periods. Note that the slideshow presentation still supported the use of locations due to the inclusion of the title list below the image presentation area (see Figure 17).

Figure 21 shows the percentages of participants that intentionally used locations for each condition. While the data do not meet the assumptions of a chi-square test for a formal analysis, the percentages do suggest that conditions did affect spatial strategies. The highest percentage of participants intentionally used locations in the persistent-visibility distributed condition, while the interactive slideshow condition had the lowest overall percentage.

We believe that the difference between automatic and interactive slideshow conditions can be explained by differences in viewing order. In the automatic slideshow presentation, the images were always presented in a linear progression. In a way, this presentation method forced participants to relate the images to their associated locations in the list. With the interactive slideshow, on the other hand, participants were able to continuously slide the mouse cursor over the list—without paying attention to location—until they found the desired image.

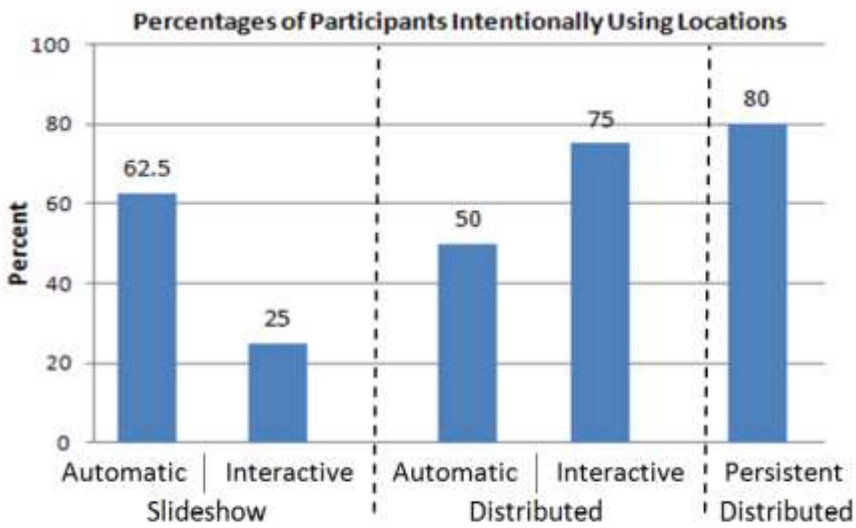


Figure 21. Percentages of participants in each condition that intentionally used locations to aid learning or recall.

5.4.7 Discussion

As hypothesized, the results from Part II confirm that learning scores with the persistent-visibility distributed layout were superior to the automatic and interactive distributed presentations. These results demonstrate the value of persistent visibility in large-display systems. Our strategy analysis helps further explain this benefit. Most participants (all but one) in the interactive or persistent-visibility conditions spent considerable time searching for specific events or characters in the data set. This certainly is faster and easier when all images are visible at the same time.

Learning scores in the persistent-visibility distributed condition were not significantly different from the slideshow conditions. Thus, for this task, we reject the hypothesis that a distributed presentation with persistent visibility supports greater learning than the slideshow style presentation. These results indicate the importance of presentation design. The experiment clearly demonstrates that a distributed spatial layout is not always an automatic method of improving cognitive processing.

Of course, this does not necessarily mean that a spatial large-screen presentation cannot support improved processing and learning of information. It is possible that our evaluation was not sensitive enough to detect differences. If participants were approaching the limit of how much could be learned in our task, this could explain why scores in the persistent-visibility condition were not significantly different. Similar experiments with larger data sets and longer learning sessions would be helpful in further investigating differences due to varying spatial presentations.

Additionally, as we discussed in the *Discussion* section for Part I, it is still unknown whether these results would differ for logically organized information layouts rather than random, jumbled organizations. If the information was meaningfully organized in space, then learners' better recall for location could potentially be used to aid information recall. This is a matter for future investigation.

The location recall results do serve as further evidence that locations can be learned automatically. However, memorization of locations was not always purely incidental with our task, as many participants did consciously pay attention to locations during learning. Still, others who intentionally attempted to use locations during questioning reported that they had not paid attention to locations during the viewing session. Also note that the results of Part II provide evidence that greater memory of locations does not negatively interfere with learning. Though the results of Part I showed that participants in the distributed conditions had higher location recall scores and lower learning scores, Part II showed that participants were able to achieve higher learning scores while still having high location recall scores.

The results from the persistent-visibility distributed condition show that learners achieved relatively high learning scores while also demonstrating high location recall, suggesting that the memory of spatial information did not interfere with the memory or understanding of the story information. Thus, designers should still consider presenting information spatially if the spatial organization can support the logical organization of the content.

These results have provided the foundation for extended research for studying the effects of spatial information distributions with large display systems. Future work includes considerations for the size of the data set, type of data representation, organization of information, and type of interactivity. We believe that the size of the data set may affect the use of spatial cues when learning. With a larger dataset, interactive view control may become necessary as users need to refer back to information on demand. Additionally, as our experiment provided jumbled presentations in order to isolate the effects of spatial mapping, the results have informed plans for future studies of varying organizational schemata. We hypothesize that logically organized information layouts could give meaning to the locations in space and allow learners to take advantage of their memories of locations for learning. Another question is whether similar results would be observed with different data representations. Our task was based primarily on graphical information that participants viewed and integrated into stories. It is possible that different results could be observed with data sets with different formats, such as textual information, rather than primarily graphical representations.

5.5 Conclusions of Experiment III

While previous studies have found that additional spatial cues have the potential to aid memorization and learning (e.g., (Hess et al., 1999; Ragan, Bowman, et al., 2012)), our research suggests that—contrary to what was expected—increasing the spatial layout complexity of information locations does not necessarily support cognitive processing. Though displaying information in spatially distributed layouts helped participants to better recall information locations, learning performance was negatively affected. This suggests that participants were unable to take advantage of their knowledge of locations to aid their learning. This disadvantage was eliminated when learners were permitted constant visibility of information, indicating the high importance of persistent visibility when working with large-displays. This suggests that spatial layouts on small displays (lacking persistent visibility and relying on virtual navigation) would lose the benefits of the spatial layout. Similarly, for 3D VEs, the results highlight the importance of easy and natural interaction for information access, which supports the hypothesis that higher spatial fidelity can be more beneficial for using spatial presentations.

6 Experiment IV: The effects of interactive view control and environmental detail on learning in 3D virtual environments

6.1 Summary

As the design of educational virtual environments serves as the primary motivation for the research, Experiment IV was designed to study spatial information presentations in a 3D world requiring travel. This study is summarized in a short paper (Ragan, Huber, Laha, & Bowman, 2012) in the *Proceedings of IEEE Virtual Reality 2012*. In this study, we focus on two design issues: level of environmental detail and degree of navigational control. In a controlled experiment, participants studied animal facts distributed among different locations in an immersive VE. Participants viewed the information with one of two methods of navigation: an automated tour through the environment or an interactive method with full navigational control. The experiment also compared two levels of environmental detail. The sparse version of the environment contained only a ground plane and large cards containing animal facts, while the detailed version also included landmark items and ground textures. The experiment tested participant memory and understanding of the animal information. While the type of navigation did not significantly affect learning outcomes, the results do suggest that manual navigation may have negatively affected the learning activity. Thus, the addition of interactivity does not always improve learning. The results also show that environmental detail had no effect on learning performance. Additionally, learning scores were correlated with both spatial ability and video game usage, suggesting that educational VEs may not be an appropriate presentation method for some learners.

6.2 Goals

The purpose of this study was to explore the relationship between visual landmarks and interactive travel. Still focusing on spatial information presentations, we studied how participants learned facts distributed among various locations within a VE. We evaluated differences in learning performance and learner strategies due to the level of navigational control and the level of environmental detail. Considering the design of the virtual content, we aim to better understand how a VE's environmental details and landmarks influence learning. Researchers have suggested that VEs could provide advantages for conceptual learning by allowing opportunities for learners to view information within the context of meaningful locations (e.g., Boulos et al., 2007; Dede et al., 2004). However, it is unknown whether a location is meaningful because of the information associated with that location or if the meaning is affected by other content at that location. Environmental details and objects could provide situational context, referring to the surroundings in which knowledge and meaning making are present (Fernandez & Glenberg, 1985; Godden & Baddeley, 1975). Through episodic memory, this context can become part of what is remembered, along with the information itself (Endel Tulving, 1993). Combined with spatial learning strategies, stronger contextual memory could directly strengthen retrieval cues.

On the other hand, as hypothesized by Jones and Dumais (1986) during their memory-of-location experiment, environmental detail could contribute to visual clutter, and potentially even interfere with the memory of the environment or the information itself. Jones and Dumais noted that the addition of landmark objects to a 2D information layout may have negatively affected memory of the locations of the information items. Our experiment investigates the effects of environmental context by comparing learning differences and learner preferences between a relatively empty VE and a VE with additional details.

Environmental details could also affect users' abilities to keep track of where certain information was located and which locations have been previously visited. Thus, this issue is closely related to the choice of an appropriate method for navigation within a VE. Our study compares interactive and automated navigation methods. Compared to automated presentations, fully manual navigation provides the freedom for learners to control the order and duration in which information is viewed, but at the cost of additional interaction and decision making.

6.3 Hypotheses

We hypothesized that having manual, interactive control of navigation would allow learners to achieve higher performance scores than those viewing the information through an automated presentation. We expected that the ability to decide how to view the information and how much time to spend learning different facts would allow more effective learning strategies. It was expected that the freedom to control the order and duration of information viewing would outweigh the additional cognitive load associated with the manual control and decision making.

For the level of environmental detail, we tested the hypothesis that additional details and landmarks would improve learning performance. This hypothesis was based on the idea that additional detail would increase the situational context of the information locations, providing stronger memory cues for later recall.

6.4 Task

To test our hypotheses, we designed a simple learning activity involving information about ten animals. The task used fictitious animals in order to avoid problems with participant familiarity with existing animals. For each animal, a fact card was provided in the VE. Figure 22 shows an example of an animal fact card. Each card had the name of the animal along with a table showing additional information about the animal (location, habitat, average weight, average body length, and conservation status). The location was always the name of a continent and the habitat was given as a short textual description. The animal's average weight was always given in kilograms and the average length was always given in centimeters. For the conservation status, which provides an indication of whether the animal is at risk for extinction (IUCN, 2001), four possible status levels were used: least concern, vulnerable, endangered, and extinct.

Forden

Location	Australia
Habitat	Desert
Avg Weight	10 kg
Avg Body Length	75 cm
Conservation Status	Vulnerable

Figure 22. An example of an animal fact card. All fact cards had the same layout, with the animal name at the top of the card (in this example, the name is *Forden*) and a table of information.

Participants were tasked with learning the animal information in the VE. The learning environment contained ten animal fact cards arranged in two rows of five cards. The complete data set is included in appendix D. Figure 23 shows a view from within the VE, while Figure 24 shows an overview of the entire environment. In virtual space, each fact card was ten feet wide and adjacent cards in the same row were positioned 20 feet apart. The two rows were separated by a distance of 60 feet.

After a learning period in the VE, participants completed tests to assess memory and understanding of the animal information, as well as memory of locations. All tests were completed outside the VE. Memory of animal facts was tested with a simple computer application that required participants to enter numerical fact values (weight and height) and select the appropriate values from drop-down lists for the other fact categories (location, habitat, and conservation status). To increase difficulty, the arrangement of the facts listed on the assessment tool was different than the arrangement of the fact card tables. This assessment covered each of the ten animals. After providing the corresponding information for the given animal name, participants could click the *Next* button to go on to the next animal. The assessment did not allow participants to go back to change their responses for previous animals.

Following the fact memory assessment, participants completed a test of information understanding. In this portion of the assessment, a computer application presented questions that required participants to think about the meaning of the information in order to select the correct animal from a drop-down list. Examples of questions are:

- Which of these animals would you expect to fit in your hand?
- Which of these animals would you expect to be most commonly found in the wild?
- Which of these animals might you find in the United States?

The understanding assessment was designed to involve thinking about the real-world meaning of the information and require more than just pure recall of facts. This portion of the assessment included 16 questions.

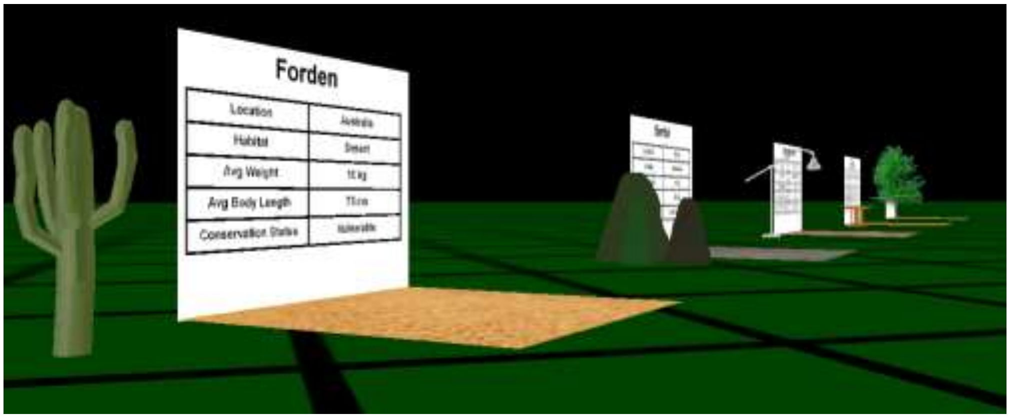


Figure 23. The learning environment contained ten animal facts cards organized in two rows of five cards. This screenshot shows the additional visuals used in the high environmental detail conditions.

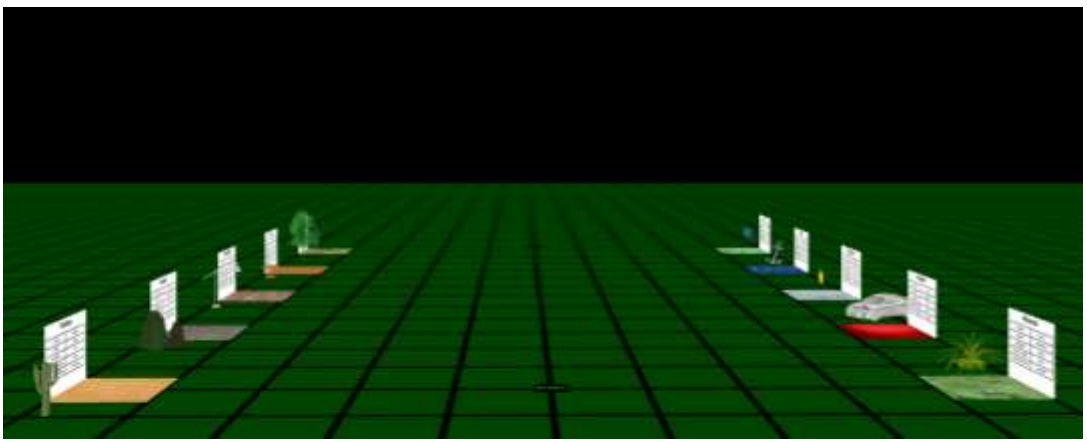


Figure 24. A view of the entire learning environment from a higher vantage point. The information cards are organized in two rows of five cards.

We collected scores and completion times for both the recall and understanding tests. Scores were calculated by awarding one point for each correct response.

Though participants were only informed of the recall and understanding tests in advance, we also tested participants on their memories of where the fact cards were in the VE. Figure 25 shows the application used for this evaluation. Based on a top-down view of the VE's layout, participants used a mouse to drag each animal name to the location where that animal's fact card was displayed in the VE. Location memory scores were calculated by counting the number of correctly placed animals. To allow participants to determine the correct orientation of the card rows for this test, the learning environment had two ground textures at opposite ends of the VE to serve as orientation markers. In the learning environment, participants started on a marker with green text reading *START*, and a marker at the other end of the VE simply showed three red dots (see Figure 25). These markers were included in the general layout of the location memory test.

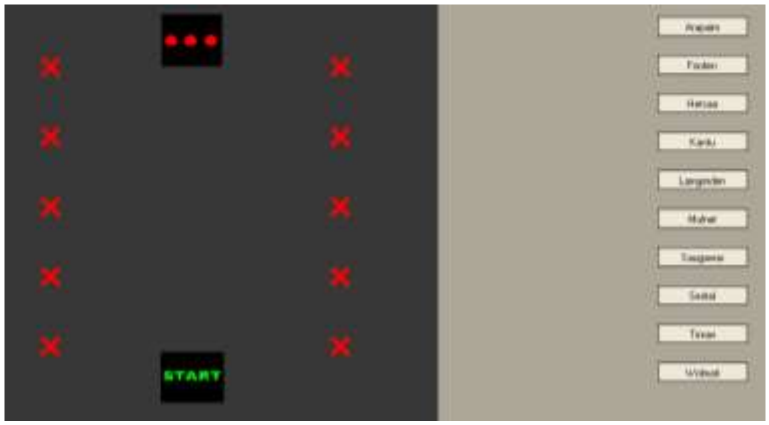


Figure 25. The software tool for assessing memory of locations. The right side has a list of labels with the animal names. The left side shows a top-down view of the card layout, with a red X marking each card location and ground decals for layout orientation. Participants indicated information locations by placing each label on a red X.

6.5 Apparatus

This experiment was conducted as an early part of a larger investigation of how design features affect learning in 3D environments. Given the emphasis on furthering the understanding of the use of locations and the perception of landmarks, a surround-screen CAVE-type display was used in order to increase the field of view and allow easier viewing of information in multiple locations. Participants experienced the learning environment within a VisBox VisCube display composed of three rear-projected display walls and a top-projected floor. Each of the four display surfaces was ten square feet with 1920x1920 resolution. Four projectors (EPSON PowerLite Pro Cinema 9500UB) were used to display visuals on each surface, with two projectors projecting overlapping images on each vertical half. Manual navigation with a wireless wand was made possible by an Intersense IS900 motion tracking system. Neither stereo nor head tracking were enabled (as these features were not directly related to the focus of this study, and enabling them would have required significantly longer familiarization time in order to limit distraction during the learning session).

Participants completed the learning and location memory assessments outside the VisCube on a laptop computer, using a standard mouse and keyboard.

6.6 Participants

Forty university students (16 male and 24 female) participated in the experiment. Participants were balanced across conditions by gender. To reduce confounds due to age or experience, we limited participation to undergraduate students between the ages of 18 and 25. Students came from a variety of academic disciplines, the most common being psychology (20 students). Each of the other disciplines had at most five students.

6.7 Experimental Design

We controlled navigation mode and environmental detail as independent variables. Participants used either an automated navigation method, in which the learner was taken to pre-recorded navigation points without any user control, or a manual navigation method, in which learners used a wand and joystick to control viewing within the VE. In both navigation modes, participants began at the same position (labeled with the *START* marker, which can been seen in Figure 25).

For the automated presentation, the view would automatically rotate to directly center the first fact card in the left row, and then move towards that card. The view would stop in front of the card for 15 seconds, and then slide to the right to focus on the next card in the row. This continued down the row in the same manner. At the end of the row, the view rotated 180 degrees and moved straight across to the other row. The view progressed down this row in the same way as the first row, stopping for 15 seconds in front of each card. The automated presentation followed this path three times, taking a total time of 9 minutes and 30 seconds.

For the manual navigation mode, the total viewing time was limited to 9 minutes and 30 seconds, so the amount of time in the learning phase was constant across conditions. To navigate manually, participants physically pointed the wand device and moved the wand's joystick forward or backward to move forward or backward relative to the direction of pointing. Movement was restricted to the floor plane. Participants could also move the joystick to the left or right to rotate the view about the center of the VisCube.

We also controlled two levels of environmental detail. In the low-detail condition, the VE contained only the information items on a green grid in a black 3D space. The high-detail condition used the same cards and environment, but each card also had a square ground texture at its base and an object beside it (as seen in Figure 23). For half of the cards, the ground textures and objects were chosen to relate to the animals' habitats. For example, an animal that lives in the desert had a cactus for its object and a ground texture resembling sand. Similarly, an aquatic animal had a boat anchor as an object and a blue texture resembling water. The other half of the cards had objects and textures that were purposely chosen to not relate to the animal information. For example, one animal had a car for its object and a bright red ground texture, while another animal had a model of a five-pointed star and a ground texture resembling marble. Cards were not spatially grouped by related and unrelated landmark types.

Both navigation type and level of environmental detail were varied between subjects in a 2x2 design. Each participant completed the entire learning activity a single time with the given combination of environmental detail and type of navigation.

Participants were only informed about the learning assessments (animal fact memory and understanding questions) prior to the learning session in the VE, but additional data was collected throughout the study. In addition to the learning and location memory scores, participants completed cube-comparison tests in order to provide a measure for exocentric spatial ability. Also, auditory number-span memory tests provided scores relating to short-term memory. Participants in conditions with environmental detail were also tested on their recollection of the landmarks and objects from the environment. In a survey before the learning task, participants also reported weekly amount of time playing video games.

6.8 Procedure

Before beginning the experiment, participants completed a brief background survey to provide basic demographic information and describe their levels of experience with technology.

With the aid of a script and paper handouts, the experimenter then explained the learning task and the types of information that would be included in the fact cards. Next, the experimenter introduced the VisCube system and further explained the learning task with the aid of a familiarization environment. The familiarization environment had the same general layout as the learning VE that was used for the primary task, but the familiarization environment contained only six cards (the primary learning VE had ten cards). Each participant experienced the familiarization environment with the same type of navigation and the same level of detail that they would use in the primary learning environment. Different animal fact cards were used in the familiarization setup, and different environmental textures and objects were used for the high environmental detail conditions. For participants in the manual navigation conditions, the experimenter trained participants on how to navigate and provided additional coaching until the participant demonstrated proficiency (participants were required to navigate to given target locations using both forward/backward movements and side-strafing).

After the familiarization session, the experimenter showed participants the recall and understanding assessment applications at a desk away from the VisCube. Participants practiced entering data and selecting answer choices in the practice application. These practice tests only contained information from the familiarization information set. The recall and understanding tests were the only tests practiced before the learning trial, as these were the only assessments that participants were to be aware of.

After the practice with the assessment tools, participants performed the learning phase in the VE for the primary task. Immediately after the learning phase, the participant moved to the nearby desk for the following assessments. The experimenter first administered a brief auditory number-span memorization test in order to help clear working memory before the information assessments. The test involved listening to a sequence of numbers and then writing down the sequence immediately after the entire sequence was read to the participant. The test included ten number sequences and took approximately two minutes. As memory research has found that retention in working memory is generally limited to around ten to fifteen seconds without active rehearsal (J. Brown, 1959; Peterson & Peterson, 1959), the number memorization exercise helped to establish that the following assessments would be completed using information from long-term memory.

Participants then completed the fact recall test and then the understanding test. Next, the experimenter explained the memory of location assessment and allowed participants to practice with an example data set (a list of names labeled *Animal 1*, *Animal 2*, etc.). Participants then completed the memory of location test. After these tests, participants were given a two-minute break before taking a cube-comparison test to provide a measure for spatial ability. Finally, the experimenter interviewed the participant about the learning task and the information tests. In this interview, participants explained preferences and complaints about the learning environments, and detailed the strategies they used to try to learn the information. For participants in conditions with environmental detail in the VE, participants were also asked to verbally list as many landmarks or objects from the environment as they could remember, providing the measure for landmark recall.

Experiment documents for Experiment IV are included in appendix D.

6.9 Quantitative Results

We tested the effects of environmental detail and navigation mode on learning scores (fact memory score, understanding score, and total score), amount of time needed to complete the learning test, and memory of animal locations. We also assessed effects on memory of landmarks for those participants in conditions with environmental detail.

Additionally, we tested for correlations among different pairs of variables. In addition to the learning and location memory scores, these tests also considered spatial ability scores, number-span memory scores, self-reported weekly video game playing times, landmark recall, and participant gender. Pearson correlations were used for metrics meeting the assumptions for parametric tests (r and p values are reported for these metrics) otherwise, Spearman correlations were tested (ρ and p values are reported for these metrics).

6.9.1 Learning Scores

A two-way independent ANOVA (analysis of variance) test of the effects on fact memory scores found no significant differences due to environmental detail, with $F(1, 36) = 0.14$ and $p = 0.71$, or navigation mode, with $F(1, 36) = 2.46$ and $p = 0.13$. Though not significantly different, the mean fact memory score was higher with automatic navigation ($M = 22.05$, $SD = 9.54$) than with manual navigation ($M = 17.85$, $SD = 6.76$). Mean scores were close between conditions with landmarks ($M = 19.45$, $SD = 7.35$) and without ($M = 20.45$, $SD = 9.56$). There was no significant interaction between landmark and interaction, with $F(1, 36) = 0.11$ and $p = 0.74$.

We analyzed understanding scores and total learning scores with non-parametric two-way Friedman ANOVA tests (as Shapiro-Wilk tests showed that these metrics may not have been normally distributed). Again, no significant effects on understanding scores were found for environmental detail or navigation mode, with F(1, 36) = 0.03 and p = 0.86, and with F(1, 36) = 2.00 and p = 0.17, respectively. However, though not significant, the scores with automatic navigation (M = 6.4, SD = 3.69) were higher than those with manual navigation (M = 4.8, SD = 3.35). Mean understanding scores were very close with landmarks (M = 5.5, SD = 3.24) and without (M = 5.7, SD = 3.96).

No differences were found for total scores, with F(1, 36) = 0.11 and p = 0.74 for environmental detail, and F(1, 36) = 2.58 and p = 0.12 for navigation. As would be expected based on the memory and understanding metrics, the total scores were higher with automatic (M = 28.45, SD = 12.83) than with manual (M = 22.65, SD = 9.21) navigation.

No significant interactions between variables were found for understanding scores, F(1, 36) = 0.78 and p = 0.38, or total scores, F(1, 36) = 0.28 and p = 0.60.

We also considered what scores might be expected if participants were simply guessing randomly. Since the fact memory scores (M = 19.95, SD = 8.43) were well above the expected value with pure guessing (M = 5.0), there is no evidence of a floor effect. The understanding scores may be less reliable, having relatively low scores (M = 5.6, SD = 3.57) compared to the expected score with guessing (M = 2.67). This suggests that the understanding assessment may have been too difficult to detect differences due to the conditions.

Though not significant, the learning score results do show that the participants generally performed better with the automatic navigation method (see Figure 26). In this experiment's time-pressured type of learning activity, it is possible that the manual navigation did increase mental workload and detracted from the learning.

6.9.2 Location Memory

No effects of environmental detail or navigation mode were found for location memory scores, with a two-way independent ANOVA showing F(1, 36) = 0.73 and p = 0.40 for detail and F(1, 36) = 1.81 and p = 0.19 for navigation. There was no significant interaction between the two variables, with F(1, 36) = 0.96 and p = 0.33. Overall, location memory scores were relatively poor (M = 4.70, SD = 2.67) and not much greater than what would be expected with guessing (M = 2.93). However, it should be noted that scoring required that participants remember the exact locations of the animal cards, even though exact location memory may not have been necessary to use locations as memory cues. Our strategy analysis showed that many participants did try to use locations to aid recall (see section 6.10.2).

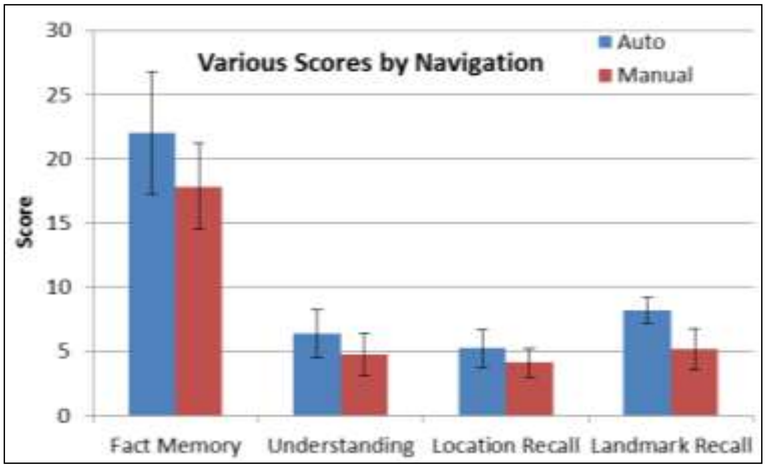


Figure 26. Mean scores and standard deviations by navigation method. All mean scores were consistently higher with automatic navigation, though only significantly higher for landmark recall.

6.9.3 Landmark Recall

For the 20 participants in conditions with environmental detail, we tested for effects of navigation method on landmark recall (memory of either ground textures or models). The one-way independent ANOVA found a significant main effect, with $F(1,18) = 6.37$ and $p = 0.02$, showing that participants remembered more landmarks with automatic navigation ($M = 8.20$, $SD = 1.93$) than with manual navigation ($M = 5.20$, $SD = 3.23$), with Cohen's $d = 1.16$ suggesting a large effect size.

Our primary explanation for this effect is that the additional cognitive effort needed for manual navigation detracted from the learning task and the perception of environment itself. This explanation corresponds to the (non-significant) trends with the learning scores and location memory metrics, where automatic navigation outperformed manual navigation (see Figure 26).

6.9.4 Spatial Ability

Testing for one-tailed correlations between learning scores and spatial ability scores (from the cube-comparison test), we found that total learning scores and spatial ability scores were significantly correlated (Pearson's ρ = 0.35, p = 0.01). Both fact memory scores (r = 0.34, p = 0.02) and understanding scores (ρ = 0.31, p = 0.03) were also each significantly correlated with spatial ability. These results suggest that participants with higher spatial ability might find it easier to learn in a VE. The spatial context of the environment might actually make learning more difficult for those with lower spatial abilities.

Spatial ability was not significantly correlated (one-tailed) with either location memory (ρ = 0.10, p = 0.26) or landmark recall (ρ = 0.34, p = 0.07). Further analysis of the effects of spatial ability, navigation, and environmental detail did not provide any evidence of an interaction for any of the metrics.

6.9.5 Video Game Activity

Reported gaming hours were significantly correlated (one-tailed) with total learning scores (ρ = 0.34, p = 0.02) and fact memory scores (ρ = 0.39, p = 0.01). The correlation neared significance for understanding scores (ρ = 0.25, p = 0.06). This is evidence that experience and practice with interactive software or in virtual spaces can affect learning in VEs.

Gaming hours were also significantly correlated with location memory, with ρ = 0.42 and p = 0.003, suggesting that experience could potentially influence the ability to use spatial learning strategies. Gaming hours were not significantly correlated with landmark recall (r = -0.05, p = 0.82).

6.9.6 Gender Effects

We tested for point-biserial correlations (two-tailed) between gender and various metrics for the 16 male and 24 female participants. A significant correlation was found between gender and spatial ability scores, with males scoring higher (r = 0.37, p = 0.02). A significant correlation was also found between gender and learning assessment completion time, with males completing the fact memory test faster (r = -0.36, p = 0.02). No significant correlations with gender were found for the times taken to complete understanding questions (r = -0.22, p = 0.20), total learning scores (ρ = 0.06, p = 0.72), memory fact scores (r = 0.04, p = 0.80), or understanding scores (r = 0.05, p = 0.78).

6.10 Qualitative Results

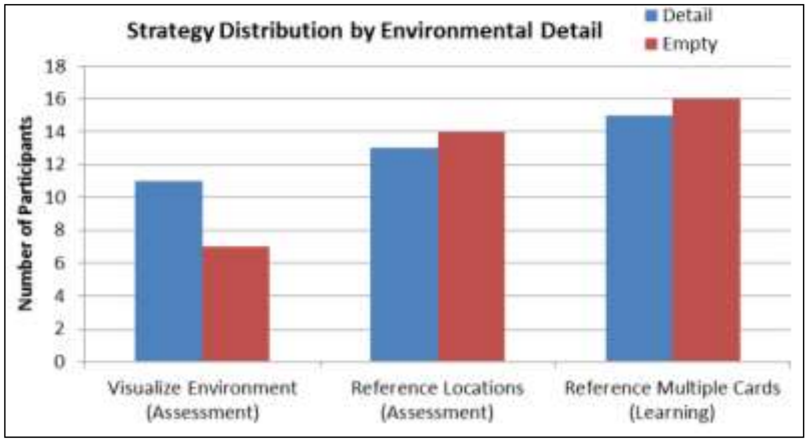
At the end of the experimental sessions, we interviewed participants about the strategies they used for the learning activity and their opinions of the VE. Based on participant responses, we identified several common strategy categories. Every participant used multiple strategies, and strategy usage does not seem to be affected by condition (see Figure 27). Moreover, correlation testing indicated that the quantitative metrics were independent of strategies, suggesting that strategy usage may mostly be a matter a personal preference.

6.10.1 General Strategies

All but one participant (97.5%) reported using rehearsal (repeating the information either out loud or internally) in the VE to aid memory. Many participants (80%) used letters or parts of the words in the fact cards to make creative associations with different facts on each card. For example, if the name of the animal started with the letter *A* and its location was Asia, they would use this association to help remember the location. Some participants (25%) tried to visualize a familiar animal or imagine a new creature to represent each animal. During the assessment, it was common (52.5%) to try to visualize the fact cards to help recall the information.

6.10.2 Location Strategies

A number of the participants (27.5%) reported that they tried to use the layout of the cards or their locations to try to remember certain details or to use locations to relate animals with similar characteristics. Similarly, during the assessment, many participants (67.5%) indicated that they did think back to the locations where the information was to aid recall. Many participants (45%) reported visualizing the environment itself or the entire layout of the cards. These results show that many learners did use spatial learning and recall strategies – even without explicit instruction to do so. Though the effectiveness of these strategies for this particular task is not clear, previous studies have shown that having information at different locations can improve recall (Hess et al., 1999; Ragan, Bowman, et al., 2012).



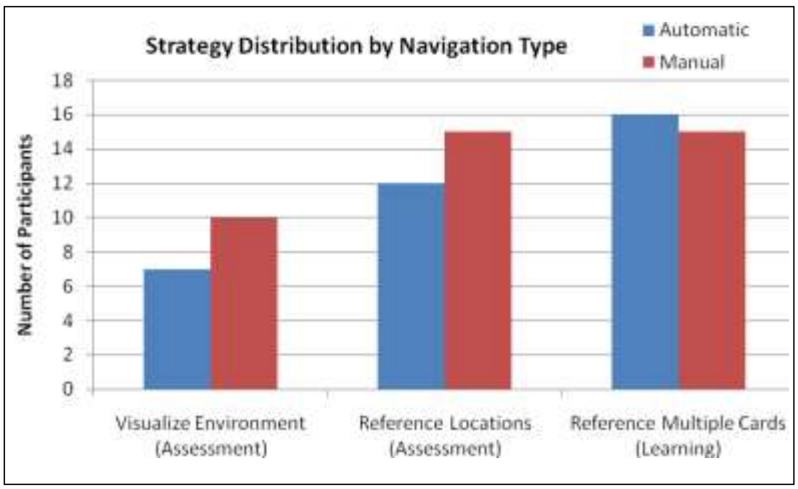


Figure 27. Distribution of select strategies by navigation method and level of environmental detail. Participants used a wide variety of strategies regardless of condition.

6.10.3 Viewing and Navigation Strategies

During the learning session, most participants (77.5%) referenced multiple cards from a single location, taking advantage of the large display size to look back at other cards, rather than always focusing solely on a single card. Several participants (17.5%) described either attempting to mentally group animals based on similarities or wanting to be able to organize the locations of the cards.

Of the participants in the manual navigation conditions, most participants (75%) intentionally tried to view multiple cards on the display at the same time either for easier comparison or to decrease the amount of necessary virtual navigation. While participants in the automatic navigation condition had no choice of the order that they viewed cards, participants with manual navigation could view cards in any order. Most (55%) of the manual navigation group used the same general viewing pattern as used in the automatic group—looping straight through all cards in sequential order. The other participants used various viewing strategies, such as studying subsets of the cards at a time or jumping to specific cards as needed.

6.10.4 Landmark Strategies and Preferences

Of the 20 participants in the conditions with environmental detail, twelve participants (60%) reported that they intentionally tried to use the landmarks or textures to help remember information during the learning session.

Participants also provided opinions of whether they found the environmental details helpful or distracting. Figure 28 provides an overview of participant opinions. Most participants did notice that some landmarks were directly related to the animal habitats and some were not. Some participants' opinions of whether landmarks were helpful or distracting depended on whether the landmarks were related or unrelated to the information. While many participants thought that related landmarks were helpful or unrelated landmarks were distracting, others found all landmarks to be distracting, while still others thought that they were all helpful. Further, the relevance of the environmental details depended on the individual. Though half of the environmental details were designed to directly correspond to the habitat in an effort to make them relevant, some participants did not find these landmarks to be relevant. In addition, some participants found that landmarks that were chosen to be unrelated were actually relevant to them.

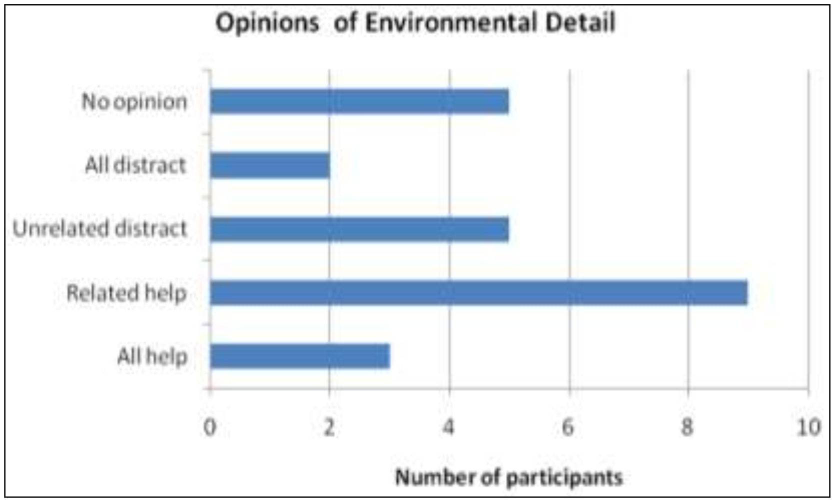


Figure 28. Participant opinions of environmental detail in the learning environment. The “Unrelated distract” and “Related help” sets are not mutually exclusive.

6.11 Discussion

Based on our results, we conclude that simple interactive view control did not significantly affect learning outcomes for simple factual learning. While highly interactive VEs may provide benefits for more complex or exploratory forms of learning, this study shows that the addition of interactivity does not always aid learning. Moreover, the significant finding for landmark recall and the trends for learning scores and location memory show better results with automatic navigation than with the interactive navigation. In this time-pressured learning activity, we suspect that manual control actually increased mental workload and negatively affected learning.

This may be related to the relatively simplistic types of navigation and viewing strategies used for manual navigation. Since many participants used the manual navigation to view the cards in an order similar to that of the automatic method, the biggest difference between viewing methods was the freedom to control how much or how little time was spent viewing each card. But this benefit of time control did not outweigh the additional overhead of movement control. In other types of learning tasks, such as those requiring comparisons of cards or determining relationships among multiple items, manual navigation may provide a greater benefit.

The results also show that the additional contextual detail of the landmarks and textures had no effect on learning performance. Thus, our results do not support the hypothesis that learning in contextual locations provides educational benefits. But this does not mean that landmarks are never useful for learning. Perhaps, for example, the environment was too simple for landmarks to have noticeable effects. Still, these findings are important when considering the value of educational VEs that do little more than present information in a 3D context. Regardless of condition, all learners viewed the same information for the same amount of time. Further investigation is needed to better understand when and how landmarks affect learning.

Of course, the lack of significant effects on learning outcomes does not prove that the conditions did not affect learning. Depending on other factors related to the use of VEs, the results could be different. For example, results could also depend on the type of display used for the VE, as previous studies have found evidence of differences in navigation proficiency between large, projected displays and standard computer monitors (Elmqvist, Tudoreanu, & Tsigas, 2008; Tan et al., 2004). Though, based on previous findings of greater benefits of automated navigation in desktop environments rather than with more immersive displays (Elmqvist et al., 2008), the effects of navigation could have been even stronger in a desktop version of this experiment.

Length of learning and retention times could also affect the results. As our entire learning session and assessment took place within about thirty minutes, it is still unknown whether interactivity or the level of environmental detail might have significant effects on learning if the learners use the application for longer periods of time. Over a longer session, it is possible that learners would begin to take better advantage of landmarks as memory cues, or use more refined movement patterns in order to focus on certain pieces of information. Since the majority of participants did refer back to the locations of the information during the assessment, it is plausible that greater familiarity with the environmental layout and landmarks could potentially allow locations to serve as stronger memory cues for the associated information. Additionally, it is still unknown how these factors affect memory retention over longer periods of time after learning in a VE. It would be interesting to study how memory of the environment and landmarks compares to the memory of the information itself at a later time. Further investigation is necessary in order to evaluate the claims of the benefits of educational VEs and the value of using locations to aid learning.

Another interesting item for consideration is whether participants can use memories of locations as memory cues for the associated information, or if knowledge of approximate location is enough.

Though the scores for memory of exact information locations are relatively low, many participants still tried to refer to fact locations to aid recall. It is unknown whether these results suggest that referencing locations was ineffective without strong memories of exact locations, or if the process of thinking back to the layout or locations actually did benefit recall.

It is possible that learners need to be trained in what learning strategies to use when learning in VEs. Though we did not instruct participants to pay attention to landmarks, participants did remember details from the learning environment. Training learners to make associations between landmarks and information might increase the benefit of spatial presentations in VEs. If using this type of strategy, since participants remembered significantly more landmarks with automatic navigation, it seems plausible that navigation method could significantly affect learning outcomes.

Our results also show that the usefulness of VEs may greatly depend on the individual learner, as learning scores were positively correlated with both spatial aptitude and video game usage. Learners with lower affinity for spatial processing or game playing might actually be less successful learning through a VE than they would be with more traditional presentations.

Further, opinions about the presence of landmarks and the nature of those landmarks clearly depend on individual preference. Multiple participants in the empty environment expressed that the VE felt empty and indicated that they would have preferred additional objects in the space. On the other hand, some participants thought that all landmarks were distracting—even those that were specifically designed to relate to the information. But others were even able to use the generic, non-related landmarks to help them remember the information.

These results suggest that it may not be possible to design a single VE that works well for everyone. Customization could be an important feature for certain types of educational VEs. We hypothesize that many learners would prefer to choose which landmarks are associated with different pieces of information. Similarly, as multiple participants discussed organization in the concluding interview, learners may also appreciate the ability to organize information in space.

6.12 Conclusions of Experiment IV

Through controlled experimentation, we studied a collection of issues to help evaluate how users learn new information within a VE. Though increased levels of interactivity may provide learning benefits for more complex or exploratory forms of learning, the results of this experiment do not support the hypothesis that that interactive navigation affects learning positively. Our results suggest the possibility that interactive control could even have negative consequences.

Though we did not instruct participants on what strategies to use in the experiment, many participants did attempt to use locations to assist in learning or recall. Additional research is needed to evaluate the effectiveness of different strategies, though previous work has provided evidence that mapping information to locations can improve recall (Hess et al., 1999; Ragan, Bowman, et al., 2012). Further investigation is needed to understand what additional factors will influence this effect.

The results also demonstrate the importance of consideration for individual differences when designing educational presentations. Even though participants were given time to practice navigation and viewing information in a VE, learning outcomes were correlated with both spatial ability and video game usage. These results suggest that an educational VE may not be an ideal presentation method for some learners. Additionally, though environmental details and landmarks had no effect on learning outcomes, opinions of the types of environmental detail varied greatly among participants. Overall, these results suggest the possibility that it may not be possible for a single environment design to provide the best support learning for any user. Further research is needed to investigate whether a more flexible and customizable VE could better support a larger audience.

7 Experiment V: Considering the degree of view control and system fidelity in spatial information exploration

7.1 Summary

As the previous experiments have studied relatively simple information layouts, we chose an application for Experiment V that fully distributes information among three dimensions. In this study, we used a data analysis task with location-contextualized scientific information environment, which broadened our research to account for another form of spatial information presentations. The findings of this study were published in the 2012 *Proceedings of Joint Virtual Reality Conference of EGVE - ICAT - EuroVR* (Ragan, Wood, McMahan, & Bowman, 2012).

This experiment further addresses the issue of view control for learning in 3D spaces, and compares partially-automated view control (a target-based travel technique) with manual control (a steering travel technique). In addition, the study compares high and low levels of spatial fidelity. With the steering technique, participants had a higher degree of control over movement, while the target-based travel technique was partially automated. We measured performance on data analysis tasks in a complex underground cave environment supplemented with additional data. The results show a significant interaction between travel technique and level of fidelity, suggesting that steering may be better suited for high-fidelity VEs, and target-based navigation may offer advantages for less immersive systems. The study also showed significantly worse simulator sickness with the higher level of fidelity, with an interaction trend suggesting that this effect was intensified by the steering technique. Though the higher degree of motion control afforded by the steering technique did allow faster data analysis, frustration and sickness also increased.

7.2 Goals

Navigation is often an essential element of VEs, especially for those based in large or complex spaces. For educational activities (as well as with any task), users should be able to focus on their primary tasks in the VE, rather than struggle with travel and wayfinding. But travelling through 3D environments can be difficult (Sayers, 2004; Smith & Marsh, 2004), particularly when natural locomotion is not available due to technological and space limitations. Even with more immersive

VEs (such as head-mounted displays or CAVEs), which often support some degree of natural physical view control through head tracking and/or surround-screen displays, many VEs still require virtual navigation methods to access different locations.

As a common solution, *steering* travel techniques allow for continuous control of the direction of movement (D. Bowman, Kruijff, Laviola, & Poupyrev, 2005) and are generally easy to understand (Mine, 1995). Nonetheless, steering techniques require adequate practice for efficient use (e.g., Ruddle, Payne, & Jones, 1997), can be slow for long distances (e.g., D. A. Bowman, Davis, Hodges, & Badre, 1999), and can cause users to become lost or disoriented within the VE (e.g., Sayers, 2004). Researchers have explored a variety of alternative travel metaphors to address some of these issues. In one such alternative, *target-based travel*, users need only indicate a specific location within the VE and the system automatically moves the user to that location (D. Bowman et al., 2005). While instant teleportation can be used for automated travel (Mohageg et al., 1996), another form of target-based travel involves moving the user to the targeted location along an automated route (D. A. Bowman et al., 1997). These target-based travel techniques have been shown to be less disorienting than the teleportation technique (e.g., D. A. Bowman et al., 1997) and to be preferred over steering when travelling larger distances (e.g., Verhagen, 2008).

Additionally, the effectiveness of travel techniques can depend on the display system itself, since the features of immersive VEs could affect the travel technique and navigation decisions. Although this line of research is primarily concerned with spatial fidelity, which is related to both display fidelity and interaction fidelity, we describe the differences in VE systems using the term *display fidelity* in the report of this experiment (we made this choice because the experiment considers additional display properties outside of the previously defined scope of spatial fidelity). *Display fidelity* refers to the objective level of sensory fidelity provided by a system (McMahan, Bowman, Zielinski, & Brady, 2012). Though prior research indicates that target-based travel may be better than steering for some immersive applications (e.g., Verhagen, 2008; Zeleznik, LaViola, Acevedo Feliz, & Keefe, 2002), these results may be limited to displays with relatively high levels of fidelity.

In order to obtain a better understanding of the effects of display fidelity on target-based travel and steering techniques, we conducted a study comparing a target-based travel technique to a pointing-based steering technique in two contrasting levels of immersion using a four-sided CAVE-type display (see Figure 29). The high-immersion conditions displayed content on all four walls with stereoscopy, and head tracking was enabled. The low-immersion conditions displayed content in mono on only one wall, and did not support head-tracked viewing.

For the context of our experiment, we implemented a data-exploration environment based on an underground cave environment. The VE was developed in collaboration with NASA as a prototype of an application for exploring extraterrestrial caves and terrains. As an *information-rich* environment (D. A. Bowman et al., 2003), supplemental visual data was presented throughout the virtual cave. We evaluated user performance for two types of data analysis tasks (searching and data relationship identification), assessed post-task memory of responses, and monitored simulator sickness.

The results of our study indicated that the steering technique allowed for faster data analysis, but with the possible risk of increased frustration and simulator sickness. We also found a significant interaction between travel technique and the level of immersion, suggesting that steering may have been better suited for the higher level of immersion in our task context. The results also indicated that the high level of immersion induced significantly worse simulator sickness than the low level, especially with the steering technique. While users might be able to achieve greater performance with manual steering techniques, partially-automated alternatives might be preferred by those who are more susceptible to simulator sickness. These results contribute towards a greater understanding of how travel techniques and the level of immersion affect both user performance and comfort in 3D VEs. Through investigation within the context of visual data exploration, this research broadens the knowledge of the relationship between displays and travel within a complex visualization environment.

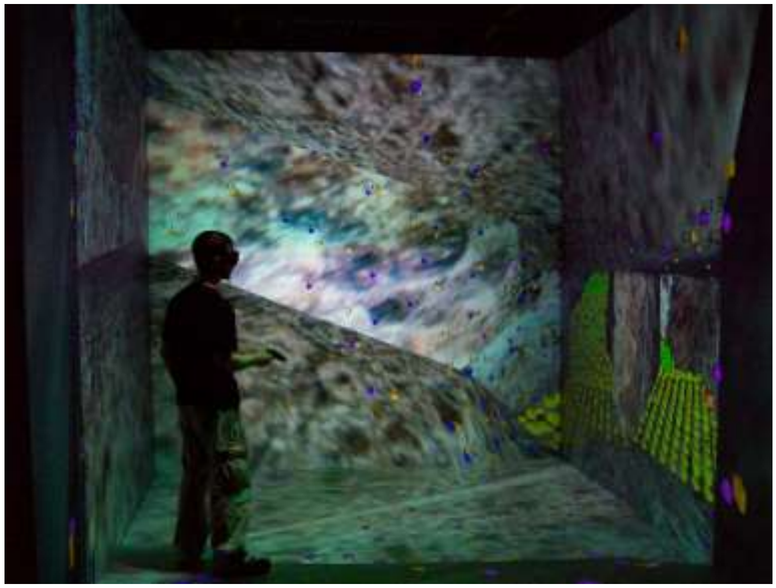


Figure 29. User in the virtual data-exploration environment.

7.3 Hypotheses

Based on the results of previous studies that showed performance improvements with navigation (e.g., Chance et al., 1998; Ruddle, Payne, & Jones, 1999), searching (e.g., Pausch, Proffitt, & Williams, 1997; 2004), and data analysis tasks (e.g., Arns et al., 1999; 2004), we hypothesized that participants would perform better on the data analysis tasks in the high-fidelity conditions. We expected that the higher FOR provided by additional display surfaces would make it easier to find minimum or maximum data values and to investigate trends and relationships among multiple data types. As previous studies have shown that physical view rotation helped users to learn spatial layouts and effectively navigate 3D spaces (Chance et al., 1998; Ruddle et al., 1999), we predicted that the high FOR would provide the same effect. In addition, we expected head tracking to help participants to more easily view around corners and obstructions to more efficiently complete the tasks. We expected this benefit to be further increased by stereoscopy, as previous research has shown increased advantages in spatial inspection tasks when stereo and head tracking are used together (Ware et al., 1993).

For travel techniques, we hypothesized an interaction with the level of display fidelity. Steering provides a higher degree of control for accessing areas and precisely manipulating the view, but efficiently controlling the view can be difficult in complex 3D spaces. As our VE was a complex cave with intersecting passageways and elevation changes, we hypothesized that steering would be problematic with low-fidelity, and that the additional display surfaces available in the high-fidelity condition would make it easier to take advantage of the increased level of control. Thus, we expected steering to allow better performance in high-fidelity and the target-based technique to be better in the low-fidelity condition.

7.4 Task

To study the effects due to the level of display fidelity and type of travel technique on a visual data analysis context, the experiment involved two types of analysis tasks in a simulated underground environment representing a cave system. The environment was supplemented with multiple types of information that were mapped to specific locations. Participants explored the environment and data to determine the answers to questions about the data points. The first task was based on a single type of data representation in isolation (i.e., one at a time), while the second explored relationships between pairs of different representations.

7.4.1 Environment and Data Representation

The experiment environment was designed to resemble an underground cave with branching passageways of open chambers of various sizes. Figure 30 shows a top-down map of the cave layout. The elevation varied throughout the cave environment, thus full 3D navigation was required to reach all areas. The VE was textured with a rocky texture, as can be seen in the views from within the VE shown in Figure 31.

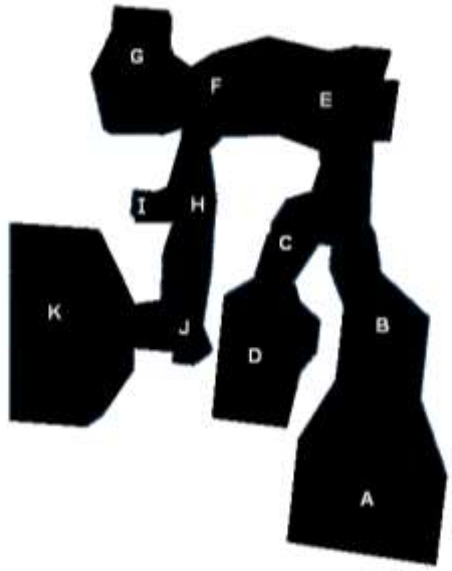


Figure 30. Top-down map of cave layout with area labels.

In addition to the geometry of the environment, the VE contained several simulated data sets that might be collected in an underground environment. Three general visualization types were used to present the data: point clouds, 3D bars, and area markers.

Temperature values were presented as points in a sparse point cloud that lined the surfaces (walls, ceilings, and floors) of the cave. Each point was represented by a small sphere at the 3D location where the temperature reading was said to be sampled. Each point had a textual label indicating the exact temperature value and was colored along a blue-red gradient, with the exact color corresponding to data value. Pure blue represented the lowest global temperature and pure red represented the highest in the environment.

Iron content was represented in a similar fashion throughout the cave, with small, labeled data points at the sample locations. Instead of spheres, these values were represented with small cubes and ranged in color from yellow (for low values) to red (for high values).

We described *sub-surface depth* as a measurement relating to density of the rock under the surface, as might be measured with ground-penetrating radar. Sub-surface depth was presented as sampled along areas of the cave floor. Values were visually represented in a fashion similar to a 3D bar graph. Each data point on the floor was represented by a bar with its height from the floor being directly proportional to its value. Like temperature and iron content, the specific numerical value was presented in a textual label above the bar. In addition, the bars also varied along a color gradient, with lower value bars being yellow and higher value bars being green.

Additionally, several large, partially transparent cloud-like spheroids were scattered throughout the VE as area markers, providing information about the general area rather than about specific point samples. Each marker had its data value presented as a billboarded text label. Three types of area markers were presented: area names, gas concentrations, and mineral concentrations. Markers of each type had consistent sizes and colors (independent of the data values)**.** Blue markers presented *gas concentrations* with numerical percentages for oxygen and nitrogen content. Orange markers presented *mineral concentrations*. The labels for these markers showed textual indicators of the relative levels of zinc and silicon content, reading as "very low," "low," "medium," "high," or "very high."

Red area markers were used to provide *area names* for certain regions of the environment. Each area name was simply an alphabetic label that corresponded to the location in the cave. Letters were unique and in alphabetical order as much as possible (see Figure 30; perfect alphabetical order was not possible due to branching passageways). The area name markers could be used as waypoints for navigation, and the area names allowed participants to easily refer to certain areas of the VE during assessments.

For interactive viewing, the data sets were grouped into four main representation groups: temperature, iron, sub-surface depth, and area markers. Each group could be individually toggled on and off by pressing a button on the wand controller, so any combination of data types could be visible at the same time.

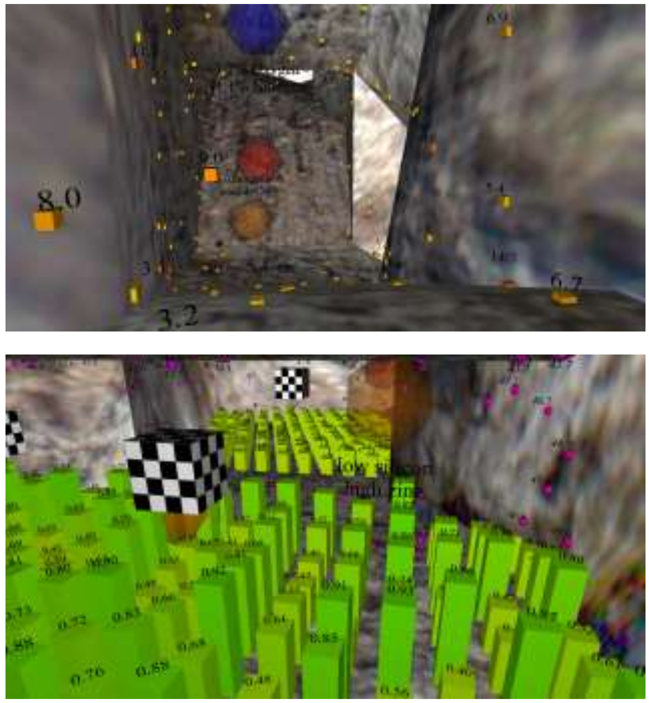


Figure 31. Two views from within the virtual cave. Small data cubes represented iron content and large area markers represented element concentrations (top). Checkered boxes were used as markers for target-based travel, green bars represented sub-surface depth, and small data points represented temperatures (bottom).

7.4.2 Search Task

In the first task, participants completed trials that each used only one data type in isolation. Participants were asked to find either the absolute highest or absolute lowest data point for the given data type. They were given up to five minutes to freely search the environment and find the data point, with regular verbal notifications of the time remaining. For each answer given, participants reported three items: the highest or lowest value found, the location of that value by the area name, and an estimate of their level of confidence (as a percentage) that the given value was correct. Answers could be given from anywhere in the VE; that is, the participant did not have to be at the correct location to give an answer.

To encourage fast responses, participants were allowed to give multiple guesses for their answer. The experimenter instructed participants to report an answer once they had reached approximately 70% confidence. After each guess (reporting the value, location, and confidence), the experimenter informed the participant if the guess was correct or incorrect. For incorrect answers, they were not told whether the location was correct—only that the entire guess was incorrect. This continued until either the participant found the correct value or the time limit was reached. To prevent random guessing, when a participant correctly reported the correct value and location, participants were then required to travel to that location and point to the correct data value. If the time expired before finding the correct value, the experimenter told participants the correct answer and required participants to move to that correct location before giving the next question. This ensured that all participants began each question from the same area.

While completing this search task, participants were also asked to remember the areas where they found the extreme values and the corresponding data type for all six questions. Post-task memory served as a metric related to mental workload and the effectiveness of the visualization condition. After completing all search tasks within the VE, participants completed a memory assessment. This assessment was conducted on a separate laptop computer and asked several questions about which areas had the highest or lowest values for a given data type. The assessment tool included a top-down map with the area letters labeled (as in Figure 30) to help participants think about the locations in the VE.

Multiple performance metrics were collected for the search task. A correctness score was calculated as the total number of questions answered correctly (with both the correct area name and the correct minimum or maximum value). Additionally, an error metric was calculated by summing the relative errors for the all questions. Relative error for each question was determined by first finding the difference between the participant's closest answer and correct answer, and then taking the ratio of that difference to the range of possible values for that data type.

Also, a time score was calculated to take speed into consideration. The time score was calculated by summing the amounts of time taken to correctly answer all questions. If the participant did not correctly answer the question within the five-minute time limit, a penalty time of ten minutes was instead added for that question.

Finally, the post-task memory metric was calculated as the sum of correct answers for the memory test.

7.4.3 Data Relationship Task

The second task built on the first, leveraging the participants' increased familiarity with the data types and locations with high and low values. For this task, participants were asked to compare two different data types and indicate if and how the data values were related through the entire cave. Three relationship types were possible: direct relation, inverse relation, or no relation. For example, if iron content was relatively high in areas of the VE where temperatures were relatively low, then iron and temperature values were considered to be inversely related. The two data types were directly related if both values were generally high (or low) in the same places. Data types were said to not be related if the relationships between high and low values were generally inconsistent among multiple locations in the cave. Because relationships were based on correlations between values throughout the entire VE, it was necessary to investigate many different areas in order to make a decision.

This task included six trials, each with a four-minute time limit. Because there were only three options for the answer, participants were not allowed to make multiple guesses; only one answer was permitted. Participants were again required to estimate a percentage for their level of confidence along with their answers. After each answer was given, the experimenter informed the participant of the correct answer.

Similar to the memory component of the search task, participants were also asked to remember the correct relationships for all questions. As with the search task, the additional in-task memorization requirement helped gauge mental workload. The format of the assessment was identical to that used in the search task, with participants supplying answers on a laptop computer outside of the VisCube. As with the search task, the post-task memory score was calculated for the relationship task as the number of correct responses on the memory test.

In addition, two performance metrics were calculated for the task. A correctness score was calculated as the sum of correctly answered questions, and the total time was the sum of times taken to answer the questions.

7.5 Participants

University students (undergraduate and graduate) and staff members were recruited as participants. We ran 39 participants in total, ranging in age from 19 to 53 (median age was 24, with three participants above 30), with a gender split of 22 males and 17 females. Participants were balanced across conditions by both gender and their reported level of experience with data analysis and scientific visualization. Twelve participants constituted the group reporting prior visualization and data experience. Participants represented a number of different disciplines (for the most common disciplines: 15 from computer science, seven from psychology, six from industrial systems engineering).

Seven participants had to withdraw due to simulator sickness, leaving 32 participants that were balanced across the four conditions (eight in each) by gender and experience. Of the participants who had to withdraw, all but one was female, and five of the seven were in the condition with high fidelity with steering navigation.

7.6 Apparatus

This experiment was conducted using a VisBox VisCube, a surround-screen CAVE-type display composed of three rear-projected display walls and a top-projected floor. Each of the four display surfaces was 10x10 feet with 1920x1920 resolution. Four projectors (EPSON PowerLite Pro Cinema 9500UB) were used to display visuals on each surface, with two projectors projecting overlapping images on each vertical half. Stereoscopy was enabled for the high-fidelity conditions through Infitec passive stereo glasses. In the low-fidelity conditions, participants wore blinder glasses that limited the field of view to match that of the Infitec glasses (the same Infitec glasses were not used to avoid issues with the passive color filtering). An Intersense IS900 motion tracking system was used to enable head tracking in the high-fidelity conditions. Both navigation techniques used a tracked wireless wand.

The VisCube was driven by four display nodes, each with two Intel Xeon E5520 2.26GHz processers, two nVidia Quadro FX5800 GPUs, and 8GB RAM. The VE was implemented in X3D and ran on the Instant Reality Instant Player. Frame rate varied depending on the number of currently visible data types, but because participants all completed the same tasks with the data, rate variability was relatively consistent among participants.

Participants completed the memory assessments outside the VisCube on a laptop computer with a standard mouse.

7.7 Experimental Design

This experiment followed a 2x2 between-subjects design for level of display fidelity and travel technique, resulting in four total conditions.

The level of display fidelity was varied by controlling the immersive display features available to participants for the tasks in the VE. The high-fidelity condition had stereoscopic rendering and head tracking, and used all four screens of the VisCube. In the low-fidelity condition, head tracking and stereo were not enabled, and only the front wall of the VisCube was used. To control for field-of-view limitations imposed by the stereo glasses, users in the low-fidelity conditions wore blinder glasses, which restricted field of view to match that of the stereo glasses.

Two travel techniques were evaluated: steering and target-based travel. The steering technique allowed users to control exact positional movements, as well as rotation around the vertical axis. Participants controlled translation by physically pointing the wand controller in the direction they wanted to travel. Moving the wand controller's joystick forward or backward allowed rate-controlled forward or backward movement in the physical pointing direction of the wand. Rate-controlled rotation was controlled by moving the joystick to the left or right.

With the target-based technique, participants could still control rotation by moving the joystick to the left or right. However, rather than having the ability to move to any position, participants could only move to one of the adjacent pre-placed waypoint locations. The cave contained 19 waypoints, represented by large checkered cubes (see Figure 31, bottom). Participants could select an adjacent waypoint by pointing towards the marker (pointing did not have to be exact, as selection was based on cone-casting). By default, waypoint markers were black and white, but a marker turned black and green when selected. Participants could then automatically transition to the selected waypoint by pressing a dedicated button on the wand. A separate button made it possible to toggle the visibility of the waypoint markers (in case the markers occluded any of the actual data).

7.8 Procedure

Participants began with a short survey to provide background and demographic information. Next, participants were given a cube comparison test from the Kit of Factor-Referenced Cognitive Tests (1976 Edition) to provide a measure for spatial ability. Participants were then introduced to the display and equipment. To explain the interaction and tasks, a practice cave environment was used. The practice VE was similar to that of the real tasks, but was smaller, simpler, and textured differently. The practice VE contained the same data representation types, but with different values and data relationships from those of the real task VE.

For participants in the high-fidelity conditions, the experimenter explained stereoscopy and head tracking, having participants practice physically moving to use the head tracking. The experimenter also taught participants how to use the travel technique chosen for their condition. Still in the practice VE, participants were given a tutorial on the different data types and how to toggle them on and off. Participants were given a paper map of a top-down view of the VE, complete with labels for area name letters, and shown how to use the area labels correspond to the layout. After this introduction and familiarization, the experimenter described the search task and guided the participant through two practice trials. The memorization component was then explained, and participants were shown an example assessment on the laptop computer.

Participants were then introduced to the real experiment environment and allowed to explore with the use of a paper map. Because participants would not have a map for the experiment tasks, participants were required to demonstrate reasonable familiarity of the VE layout before beginning the search task. For this, the experimenter required that participants successfully travel to several specific areas without the map.

Participants then completed the search task, followed by the memory assessment. After a short break, participants were then instructed on the relationship tasks and performed two practice runs in the smaller practice environment. They were given a moment to regain their bearings in the real environment before completing the data relationship task and the memory assessment. Finally, the experimenter verbally interviewed participant about task strategies, challenges, preferences, and any sickness or discomfort. The entire experiment session lasted approximately two hours.

Study approval documents, questionnaires, task instructions, and questions for Experiment V are included in appendix E.

7.9 Results

We analyzed the results of both experimental tasks to test for effects due to the level of display fidelity and travel technique. In addition to task performance metrics, we also considered participant simulator sickness, spatial ability scores, gender, and data analysis experience. For effect testing, we concluded that independent factorial ANOVA (analysis of variance) tests were the best choice for statistical analysis of performance metrics. While not all metrics met the assumptions of normality and homogeneity of variance, the alternative non-parametric methods (ordinal logistic regression with maximum likelihood estimation) fitting our experimental design were not appropriate for our sample size (see (Eliason, 1993; Long, 1997)).

7.9.1 Search Task Results

An independent factorial ANOVA for effects of travel technique and fidelity on search correctness score found a significant effect of fidelity, with $F(1, 28) = 6.81$ and $p = 0.01$. Correctness scores were significantly higher with low fidelity ($M = 5.38$, $SD = 0.81$) than high fidelity ($M = 4.63$, $SD = 0.81$), with Cohen's $d = 0.93$. The test found no effect due to travel technique, with $F(1, 28) = 0.76$ and $p = 0.39$, and no interaction between travel technique and display fidelity, with $F(1,28) = 0.76$ and $p = 0.39$.

The ANOVA for effects on error also found a significant effect of display fidelity. The low fidelity conditions ($M = 0.02$, $SD = 0.04$) had significantly lower error than high fidelity ($M = 0.16$, $SD = 0.23$), with $F(1, 28) = 6.0$ and, $p = 0.02$, though the effect size was small ($d = 0.10$). No significance was found for the effect of travel technique, with $F(1, 28) = 1.85$ and $p = 0.19$, though the target-based technique ($M = 0.05$, $SD = 0.07$) did have lower error than the steering technique ($M = 0.13$, $SD = 0.24$). No significant interaction was found, with $F(1, 28) = 0.84$ and $p = 0.37$.

The ANOVA for time scores found no significant effects for either display fidelity, with $F(1, 28) = 2.78$ and $p = 0.11$, or travel technique, with $F(1, 28) = 1.83$ and $p = 0.19$. Though not significant, the low display fidelity conditions had faster times ($M = 1105$, $SD = 548$) than the high fidelity ($M =

1392, SD = 421), and the steering conditions had faster times (M = 1132, SD = 531) than the target-based travel (M = 1365, SD = 458).

For post-search memory, the ANOVA found a significant interaction between travel technique and display fidelity, with $F(1, 28) = 5.46$ and $p = 0.03$. Figure 32 shows the interaction. A post-hoc Student's t-test indicated that the condition with high display fidelity and steering was significantly different from the low-fidelity condition with steering (Cohen's d = 1.07). Considering the memorization component as a secondary task to the primary search task, the memorization results could be attributed to differences in mental workload while navigating. The interaction graph (see Figure 32) suggests that steering may be better suited for high-fidelity VEs, and target-based travel may offer advantages for less immersive systems.

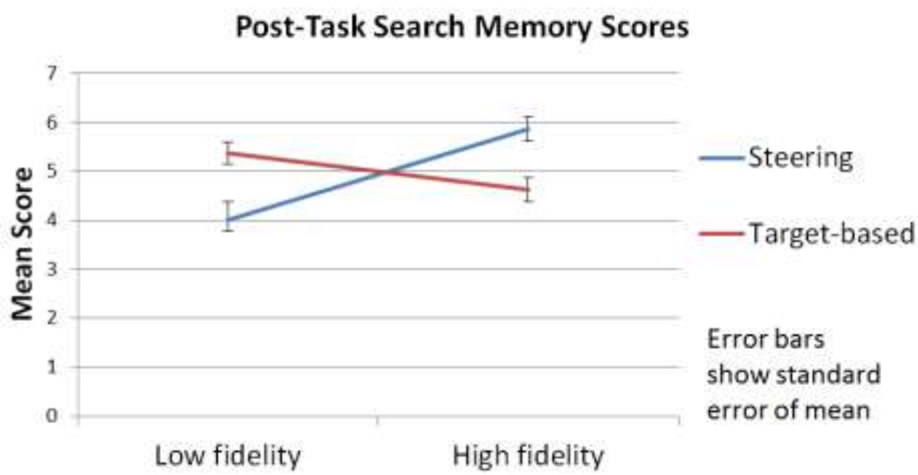


Figure 32. Interaction effect between travel technique and display fidelity for search memory scores.

We also tested for correlations with reported computer usage, reported gaming hours, experience with visualization and data analysis, and spatial ability scores. A one-tailed Spearman's correlation showed that search correctness scores were significantly correlated with gaming hours ($\rho = 0.35$ and $p = 0.02$). A significant one-tailed correlation was also found between time scores and gaming hours ($\rho = -0.332$, $p = 0.03$). These correlations show that participants who played more games generally had superior performance in terms of both time and accuracy.

No significant correlations with the task metrics were found for the other factors.

7.9.2 Data Relationship Results

An ANOVA for effects of travel technique and display fidelity on relationship correctness scores found no significant effects for travel technique, with $F(1, 28) = 1.07$ and $p = 0.31$, or for display fidelity, also with $F(1, 28) = 1.07$ and $p = 0.31$. No interaction was detected, with $F(1, 28) = 0.04$ and $p = 0.83$.

An ANOVA for total task time found a significant effect of travel technique, with $F(1, 28) = 4.92$ and $p = 0.03$, showing that participants performed significantly faster with the steering technique ($M = 696$, $SD = 218$) than with the target-based technique ($M = 879$, $SD = 239$), with $d = 0.80$. No significant effect on task time was found for the level of display fidelity, with $F(1, 28) < 0.01$ and $p = 0.96$, and no significant interaction was found, with $F(1,28) = 0.13$ and $p = 0.72$.

Testing for effects on post-task relationship memory, an ANOVA found no significance for travel technique, with $F(1, 28) = 0.50$ and $p = 0.49$, or for display fidelity, with $F(1, 28) = 1.62$ and $p = 0.21$. There was no evidence of an interaction between the variables, with $F(1, 28) = 1.62$ and $p = 0.21$.

As with the search results, we also tested for correlations with experience with visualization and data analysis, reported computer usage, reported gaming hours, and spatial ability scores. Tests found no significant correlations with metrics for the relationship task.

7.9.3 Simulator Sickness Results

Though we did not expect high levels of discomfort and it was not our intention to evaluate simulator sickness, many participants did experience discomfort or sickness. Before the experiment began, participants were informed of the risks of sickness in the VE and were asked to report any discomfort at any time during the study. The experimenter also asked participants how they were feeling after tasks, making sure they knew they had the option to stop at any time. Though analysis of the effects of travel technique and level of display fidelity only considered the 32 participants who completed the entire experiment (all questions from both the search and relationship tasks), the seven participants who stopped the study early due to sickness were also considered for the simulator sickness effects. In addition to reports during the experiment, the exit interview also asked about any negative symptoms.

A simple simulator sickness metric was calculated by assigning a sickness rating from zero to three. A rating of zero was given for no reported sickness or discomfort. A rating of one was given for slight discomfort (e.g., minor headache or eye strain). A rating of two was given for a level of discomfort that was high (e.g., nausea or more severe headache), but tolerable enough to complete the experiment. A rating of three was given for participants with sickness levels so high that they did not finish the study (either by the experimenter's judgement or by their own choice).

We tested for effects of travel technique and display fidelity on sickness with two-way ordinal logistic regression. The likelihood ratio test indicated a significant effect of display fidelity, with $\chi^2 = 7.34$ and $p < 0.01$. The test found no significant effect of travel technique, with $\chi^2 = 0.08$ and $p = 0.77$.

The test also found no significant interaction between travel technique and display fidelity, with $\chi^2 = 2.18$ and $p = 0.14$. However, we suspect that the interaction could have been significant with more participants. Figure 33 shows this interaction graphically. In the two high display fidelity conditions, sickness was worse with the steering technique, though travel technique did not seem to affect sickness levels in the low display fidelity conditions. We hypothesize that the additional movements allowed by unrestricted manual control (i.e., the abilities to change elevation level at will, move along swerving or jagged paths, or collide with surfaces) intensified the discomfort associated with the more immersive display conditions.

Another possible explanation for the higher levels of sickness in the condition with high fidelity and steering-based travel could relate to participant gender. A two-tailed point-biserial correlation between gender and sickness showed that female participants had significantly higher levels of sickness, with $r = 0.38$ and $p = 0.02$. This result agrees with other documented cases where females became sicker than males in VEs (e.g., Jaeger & Mourant, 2001; Mourant & Thattacherry, 2000). For our evaluation of effects on task performance, we balanced participants across conditions by gender for the 32 participants who completed the entire experiment. A participant who did not finish was replaced by another participant of the same gender. Participants who had to stop early were not included in the analysis of task metrics since they provided incomplete data, but they were included in the analysis of sickness effects. In our study, multiple females in the condition with high display fidelity and the steering technique got sick and stopped early, resulting in more females to replace them in this condition. Consequently, gender was not balanced for the analysis of sickness effects, and gender was confounded with the experimental conditions for the simulator-sickness analysis. Thus, while females did experience worse sickness overall in our study, this could have been a side effect of the higher fidelity, since more females were in the high display fidelity conditions.

Relating back to the task performance results, the sickness effects could explain the significant search performance detriment due to higher display fidelity. Considering only the 32 participants who completed the entire study, a non-parametric Spearman's test did show a trend between search-correctness scores and sickness. With $\rho = -0.30$ and $p = 0.10$, participants experiencing worse sickness did tend to earn lower search scores (though not significantly).

We also tested for a relationship between reported video game usage and sickness. We found no significant correlation, with $\rho = -0.03$ and $p = 0.88$.

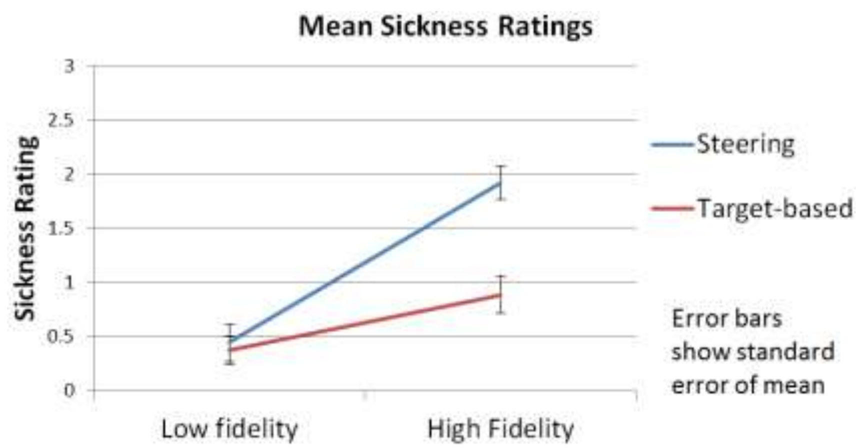


Figure 33. Interaction between travel and display fidelity for simulator sickness.

7.10 Discussion

While many controlled studies have found evidence of the potential benefits of immersive VEs for a variety tasks (including navigation and data analysis), our results show that these effects depend on other factors beyond display features. The results of the search task in our study show that performance (in terms of correct identifications) was significantly worse in the high-fidelity conditions. We suspect that this was due to the simulator sickness effects, as sickness was also significantly worse with high display fidelity. Thus, this study shows that it is important to consider the costs (in this case, sickness) for real-world data-analysis tasks when trying to improve performance through increased fidelity. Though the increased FOR provided by more screens in the high fidelity condition allowed for physical rotation and may have made visual scanning easier, it also may have been visually overwhelming—especially with the motion associated with travel.

Discomfort with the visual experience may have been worsened by the unfamiliar geometry of the environment, which had jagged-edged walls, irregularly sized pathways, dips, and inclines. Many participants provided specific details about what features of the VE they believed to contribute to their discomfort. Multiple participants reported that the changes in elevation were the most unsettling. This response was worse in the high- fidelity conditions due to the floor projection surface, and some participants even physically stumbled in reaction to elevation changes. The texturing of the virtual cave was also mentioned, which agrees with previous findings of sickness problems due to textures (Jaeger & Mourant, 2001). Further, several participants mentioned that they felt worse when travelling faster.

As for the travel techniques, the higher degree of navigational control afforded by the steering technique did allow faster performance in the data-relationship task. Steering helped participants to continuously scan areas of the VE to compare data types, which we believe made it easier to identify relationships, while the target-based travel lent itself towards more segmented inspection. However, sickness results suggest that steering also increased the risk of simulator sickness in the high-fidelity condition (see Figure 33). Our observations and interviews led us to believe that this was primarily because steering allowed both translation and rotation simultaneously, which previous research has shown can be problematic and lead to sickness (Bonato, Bubka, Palmisano, Phillip, & Moreno, 2008). The target-based method, on the other hand, separated translation and rotation—automating translation to waypoints and only allowing view rotation from a static position at a waypoint. To add to the problems with steering, the higher degree of control allowed participants to make jagged movements, creating more jarring visual experiences. Steering also made it possible to collide with the surfaces of the virtual cave, which introduced unexpected pauses in motion.

The significant interaction between travel technique and level of display fidelity for the search task's memorization component suggests that pointing-based steering may be better suited for high-fidelity VEs, and target-based travel may offer advantages for less immersive systems. We hypothesize that the pointing-based steering was easier with high-fidelity because of the additional display area available with all four screens. It was surprising that the memory results did not show evidence of benefits of increased display fidelity for target-based travel, since we expected the physical rotation supported by the surrounding FOR to make it easier to find and point to waypoint markers. However, this finding was similar to the interaction effect observed in the navigation study by Elmqvist et al. (Elmqvist et al., 2008) for varying levels of steering control.

For navigation in real VE applications, the speed benefits of steering may not be worth the discomfort. However, as many participants did not experience sickness effects, many users of real applications could potentially take advantage of greater motion control without negative consequences. Our results suggest that target-based travel (or other partially automated travel techniques) may be more appropriate for users who are more susceptible to simulator sickness.

7.11 Conclusions of Experiment V

Travel in complex 3D VEs can be difficult and disorienting, and can even induce sickness. By studying the relationship between travel techniques (steering vs. target-based travel) and the level of display fidelity (high vs. low) in a controlled experiment, our work contributes to a better understanding of the tradeoffs between task performance and user comfort for tasks in 3D spaces. In our study, participants completed two data analysis tasks in an information-rich virtual cave. The results showed worse performance in the high display fidelity conditions, which we suspect was due to the increased levels of simulator sickness induced by the immersive display features. While the steering technique helped participants to more quickly identify relationships between data types, steering also intensified sickness responses in the high-fidelity condition.

While interviews with participants revealed multiple explanations for the high levels of simulator sickness, additional studies are needed to test methods for reducing sickness effects. For example, as the floor display surface seemed to cause discomfort with elevation changes, it would be interesting to study whether participants would actually prefer to travel in a surround-screen VE without a floor.

Another issue for consideration is how the nature of the visual data analysis task affected the results of our study. Because of the task's data representations, participants were almost always looking through a large number of visual objects with irregular distributions and contrasting colors. Future research could investigate whether a more sparse or simplistic VE would affect the impact of the immersive display components or the ability to effectively navigate with different techniques.

8 Case Study for Designing Spatial Information Presentations

8.1 Summary

Based on the findings of the five experiments, this step involves a case study for the use of spatial information presentations to support learning. Our previous studies have been tightly controlled evaluations of specific design factors (e.g., spatial vs. non-spatial distributions, 1D spatial distribution vs. 2D spatial distribution, surround-screen display vs. single screen, automated viewing vs. interactive viewing). But to allow controlled evaluations, the learning activities were often limited to those that suited the goals of the experiment. In a case study, we took the principles learned about spatial information presentations from previous studies and applied them in the development of an educational environment for learning a real history lesson. We then conducted a small usability evaluation to refine our developed design guidelines.

8.2 Goals

This research explores design factors for 3D educational environments and considers factors such as information layout, environmental detail, travel techniques, and spatial fidelity. As a case study in design, we went through the design and development process for a more realistic educational application. With this approach, our goals were to refine our design principles and to better understand how they could be applied to real applications.

Because application use and design can be affected by differences in display characteristics and interaction techniques, we chose to develop both a laptop version and a more immersive version of the educational application. We sought to investigate whether differences between systems affect how learners explore the information space and make sense of spatially-presented information, and we wanted to explore how effective the same spatial design would be when applied to both types of displays.

After the design and development of the application, the case study included a small usability evaluation of the application design. For this evaluation, we asked six participants to use the application for a learning activity. After this activity, we interviewed participants about specific design factors, their learning strategies, preferences, and opinions about the application. The collected data help us to evaluate and refine design the guidelines for spatial information presentations.

8.3 Task and Lesson Design

We sought to refine design guidelines for presenting information at locations to support learning. As such, this exercise would be trivial if the information lent itself to an obvious spatial organization. We expected that we could learn more from a learning activity that lacked a clear presentation method. Further, we aimed to study a fairly complex topic that went beyond simply reading and memorizing facts. We chose a history lesson about the causes of the First World War. The information was designed to help learners respond to the following prompt: *Explain the causes of the First World War, and include both short-term and long-term causes. Your account should also explain who you think was responsible for war.* The causes of the war are messy and involve a large number of countries, events, and sources of tension. Further, by asking learners to assign responsibility for the war, we encouraged learners to analyze the many causes together and to justify an argument for blame. Because the presented lesson did not present a single clear assignment of blame, learners needed to evaluate the available evidence to construct their justifications.

To ensure that our choice of task was a realistic learning activity, the lesson and the prompt were based off of questions from an exam for the General Certificate of Secondary Education (GCSE) in Modern World History. The informational content and much of its organization in the educational VE was based off of the chapter, *The Causes of the First World War*, in the textbook, *GCSE Modern World History: History in Focus* (Walsh, 2001).

The organization of the material for our application was based on the main causes organized in subsections of the book chapter. Informational items were represented across 39 *cards* (i.e., textured rectangles) distributed throughout the COWWI (causes of WWI) environment. On the cards, items were presented as a combination of text, graphs, maps, and other images (see Figure 34). The VE was organized between two main areas: the *main area* and the *map area* (see Figure 35). In the *main area*, cards were organized into eight subgroups of related information, with each group having between two and five cards. Each group included a billboarded textual label with a name related to the content of the group. For example, the group with information about country alliances was labeled *Alliances*. In addition, each group included a landmark image to help make the content of the group more memorable and more easily recognizable from a distance. For example, the *alliances* group had an image of a hand shake.

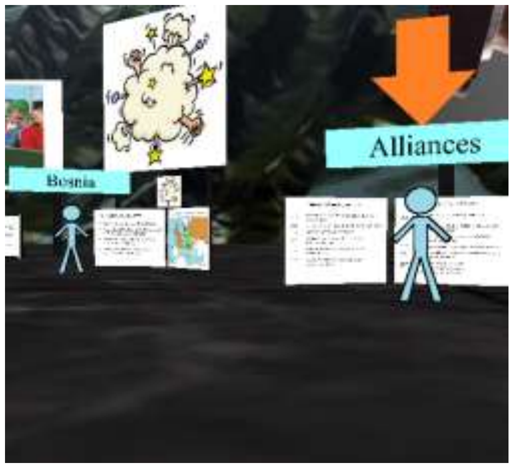


Figure 34. Information cards within the virtual environment. View locations were marked with blue "person" markers, and an orange arrow showed the currently selected target.

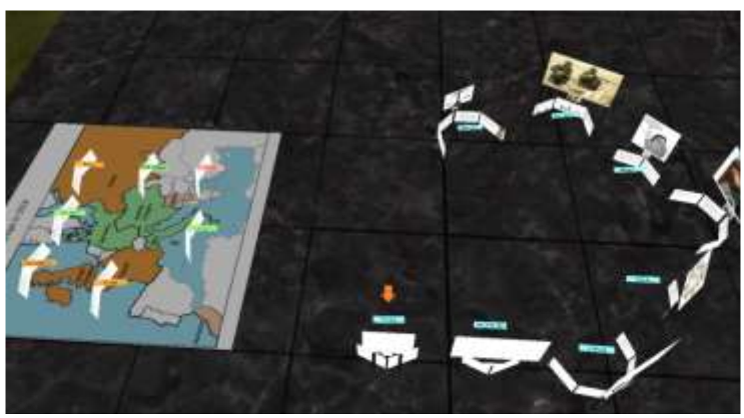


Figure 35. The layout of the COWWI VE from a high view.

The *map area* contained a large map of Europe on the floor and another large vertical map that was visible from anywhere else in the VE. On the floor map, cards were organized into seven groups, each for a country with major involvement in leading up to the war. Countries were positioned near their geographical locations on the map (see Figure 36). Each country group contained two cards: one for relevant *background* notes and one with relevant *interests and issues*. Each country group was labeled with the billboarded text of the country's name. Both the country labels and the countries on the map were color-coded to match the major alliances.

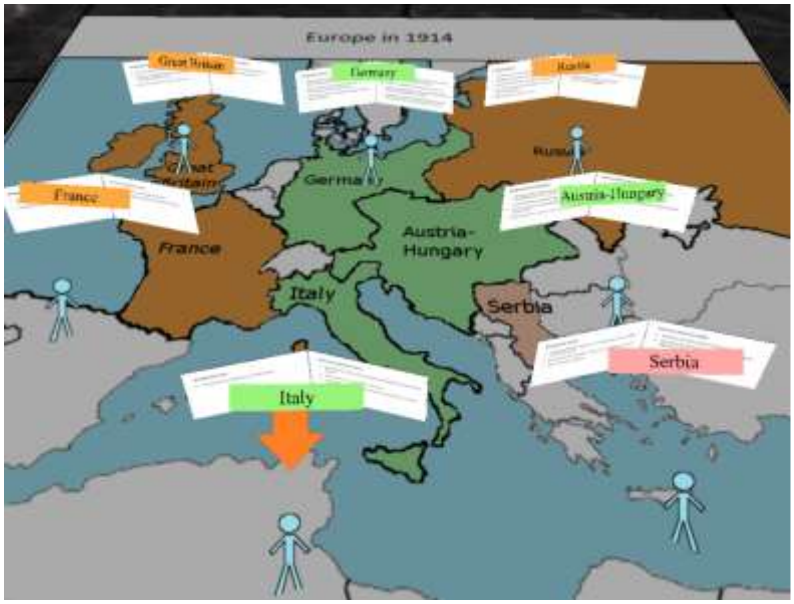


Figure 36. View of the map area from the elevated viewpoint.

8.4 Apparatus and Interaction

Two versions of the application were implemented: one for a laptop and one for a CAVE-like VisCube display.

8.4.1 Laptop Implementation

The laptop had 14-inch screen with 1366x768 pixel resolution. A standard mouse was used for interaction. Similar to most first-person video games, moving the mouse allowed participants to look around by rotating the camera about the current virtual position. Moving the mouse left or right adjusted heading, while moving the mouse forward or backward adjusted pitch. Pitch was limited to 80° from the horizontal (in either direction) to prevent disorientation issues from looking straight up or straight down.

A target-based technique was used for translation. Users could only move to the predefined view locations, which were marked with billboarded blue person markers (see Figure 34). Users could select a view location by moving the mouse to face the person marker at that location. The location was automatically selected when a view location was close to the center of the view, and an orange arrow appeared over the selected marker to clearly show the selected location. By left clicking with the mouse, the user would automatically transition to that selected location. Transitions were linear interpolations over a period of one second.

The user could also right click to transition to the closest elevated view location. Right-click transitions did not depend on the selected location. When on the ground, right clicking moved the view to the closer of the two elevated viewpoints. If the user was already in an elevated viewpoint, right clicking would transition to the other elevated viewpoint.

8.4.2 VisCube Implementation

The other version ran on a VisBox VisCube display, a CAVE-like display with four screens (three rear-projected display walls and a front-projected floor). Each screen was 10x10 feet and had 1920x1920 pixel resolution. Neither head tracking nor stereo were enabled for this application. A backless swivel chair was also available to users in the VisCube version of the application (Figure 37), but participants had the option of sitting or standing.

Figure 37. The COWWI application in the VisCube.

For interaction in the VisCube version, participants used a wireless handheld wand controller. The wand had a joystick and four front buttons that could all be used by the thumb. It also had one trigger button that could be pressed with the index finger. Users could move the joystick to the left or right to rotate the virtual view accordingly. In order to maintain a consistent matching between the virtual and the physical environments, pitch was not adjustable.

For translation, target-based travel worked similarly to the laptop application with person markers at view locations, but raycasting was used for selection. The wand was tracked in six degrees of freedom with an Intersense IS900, which allowed control of the position and orientation of a virtual selection ray. As in the laptop application, a target location was marked with an orange arrow when selected. The user could press the trigger button to travel to the selected location with a one-second interpolation. Users could press any of the other four wand buttons to travel to an elevated viewpoint.

8.4.3 Differences between Laptop and VisCube Versions

For the purposes of this case study, we sought to study whether the same information layout would work similarly for both displays. For this reason, we kept the applications identical in terms of content, information presentation, and the choice of target-based travel. However, as a case study, we wanted to develop real, usable, and well-designed educational applications for both platforms. A surround-screen system and a laptop computer obviously have many differences, and several design specifications were customized for the display systems.

i Pitch control

The laptop version of the application supported both heading and pitch rotation via mouse movements, but the VisCube version did not allow virtual pitch rotation (only heading rotation was possible with the wand joystick). For the laptop version, allowing pitch control helped users to have greater overall control of the view through the small screen. Additionally, it was necessary in order to look down from the elevated viewpoints.

In the VisCube, on the other hand, the surround-screen display—and especially the floor—made it possible to see down from the elevated viewpoints without virtually adjusting pitch. Further, not allowing pitch changes in the VisCube ensured that the virtual pitch would always match that of the physical display. This prevented potential disorientation problems that could arise from a mismatch between the user’s physical position and the virtual orientation shown on the surrounding walls and floor.

ii Orientation interpolation

Related to the difference in pitch control, interpolations between travel locations worked slightly differently in the two versions of the application. The laptop version automatically interpolated between both position and orientation when transitioning between two view positions. With the limited size of the screen, it was clear which general direction the user should be facing when moving to another location.

In contrast, travel only interpolated between translations in the VisCube; orientations were not automatically adjusted. This decision was again due to the surround-screen nature of the VisCube display. With the large display area, it was not obvious which screen should have the focus when automatically transitioning to the new location. This could have required users to make additional physical body rotations to compensate for unexpected changes in focus. Additionally, we worried that automatically adjusting the orientation to an arbitrary wall would encourage greater reliance on virtual rotation, which would discourage the use of physical rotation and undermine one of the major potential advantages of the surround-screen display (i.e., the use of physical head and body rotation for natural and familiar viewing).

iii Locked view in map area

A large area of the environment was devoted to a map of Europe. This map area contained a large vertical map that was visible from anywhere in the environment. In front of the vertical map, the same map was shown horizontally on the floor. Information stations were located near certain countries on the map that were involved with the presented causes of WWI (see Figure 36). We considered the possibility that users would be able to refer to the floor map while moving directly between country stations in the map area. This worked fairly well in the VisCube version of the application, as the floor screen and additional walls made it easy to see a large portion of the floor map when standing on it. However, preliminary testing with the laptop version found that such direct travel made it difficult to find other country stations while on the map. Further, it was difficult to maintain knowledge of the country layout from unfamiliar orientations of the map. To avoid these problems, travel and view control was constrained in the map area for the laptop version. Rather than having the option of directly facing a different country target while standing on the map (which would alter the orientation of the ground map), view control was locked while standing on a country. Instead, users could only select a country from the elevated viewpoint above the map area, which granted a clear and familiar view of the entire map and the locations of the country stations. This view made it easier to find countries, as their locations were close to their geographical locations on the map. When a country station was selected, the user would automatically interpolate to that location, as usual. However, once at the country station, the user could only travel back to the previous elevated viewpoint, and any mouse click would automatically initiate this transition without the need for selection.

The VisCube version of the application still supported a similar viewing method through the use of the elevated viewpoint above the map area, but users also had the option of directly traveling between countries without traveling back to the elevated viewpoint.

8.5 Participants

Six participants completed the study. Two were female and four were male. Ages ranged from 21 to 31. All participants were asked to rate their knowledge of WWI on a scale from one (low knowledge—*I have no idea when it was or who was involved*) to seven (high knowledge—*I am very confident about my knowledge of WWI*). As Figure 38 shows, no participant reported greater than four, showing low confidence in prior knowledge of the topic. Participants also completed an eight-question multiple-choice test about the war prior to the exercise, and participant percentages of correct responses ranged from 25% to 50%. We use these metrics as simple indicators that none of the participants were highly familiar with the learning topic. Three participants completed the experiment with the laptop version of the application, and the other three used the VisCube.

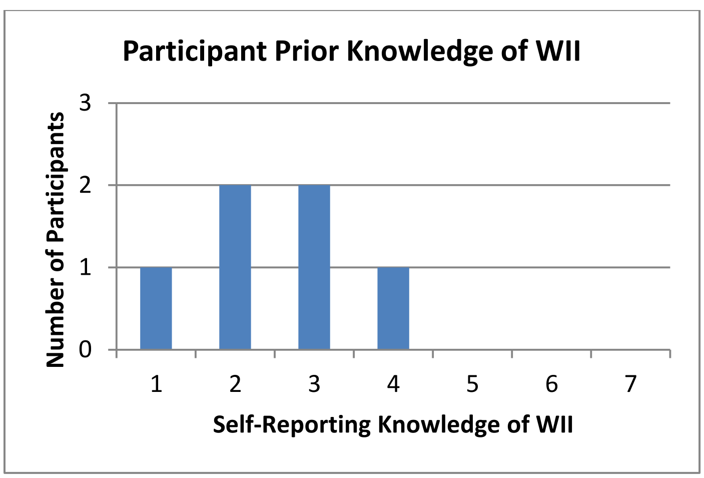


Figure 38. Self-reported participant knowledge of WWI.

8.6 Procedure

Participants first completed a background questionnaire to collect information about demographics, experience with technology and video games, and knowledge of WWI. Next, participants completed an eight-question multiple-choice test about the causes of WWI. After this, the experimenter explained the learning task, showed the participant the essay prompt, and explained the essay writing that would follow. The experimenter then introduced participants to the technology using a version of the application with all information missing. All text and images related to the task were shown as empty white placeholders. With this empty environment, the experimenter instructed the participant on how to interact and travel within the environment, and the participant had the opportunity to practice. Following, the participant completed the learning phase of the activity, which consisted of up to 20 minutes using the application (participants could stop early if they wanted, but were asked beforehand to spend at least 10 minutes in the VE). After the learning phase, the experimenter closed the application and participants completed the same multiple-choice test that they had previously taken. Participants then completed a simulator sickness questionnaire (R. S. Kennedy, Lane, Berbaum, & Lilienthal, 1993) to help gauge any adverse reactions to the VE.

Participants then used Microsoft Word on a separate laptop computer to write essays explaining the causes of the First World War. For this writing phase, participants had access to a blank version of the application. This way, participants had the option of visiting locations and adjusting the view of the environment as a memory aid, but none of the information was visible. This version of the environment was the same as the one used in the familiarization and practice, except its empty information cards were labeled with large letters and numbers to help participants verbally describe specific items to the experimenter (this helped to determine memory of locations, which is described in the following paragraph). The writing phase of the experiment was limited to 20 minutes.

Next, the interviewer verbally interviewed each participant to collect information about learning strategies, viewing strategies, problems and preferences with the application, and anything else that the participant wished to discuss. Finally, participants were asked to move around in the blanked-out version of the VE and recall where information was presented. Participants pointed to the blank items and verbally described the content of as many locations as they could remember. The entire experiment lasted between 90 and 120 minutes.

Experiment documents for this study are included in appendix F.

8.7 Results

In this section, we present the task results for learning outcomes, sickness effects, and general user strategies. The primary concern for this study was to learn more about design guidelines for the use of space, which we will present in the next chapter. The results reported in this section are provided for completeness and to help better explain the learning activity and user behaviors.

8.7.1 Learning Outcomes

Outcome measures included the multiple choice test scores and the essay results. Figure 39 shows the multiple choice test scores from both before and after the learning activity with the VE. This test contained accepted facts about the war. The pretest scores show that, overall, participants had a relatively little prior knowledge of the topic, with M = 3.333 and SD = 0.816 out of 8.0 possible points. This data agrees with the self-reported ratings of prior knowledge, showing that the participants were only able to correctly answer between two and four of the eight questions. The posttest scores show that all participants did improve their scores from the pretest, and the descriptive statistics show M = 6.50 and SD = 1.05. However, only one participant answered all questions correctly in the posttest.

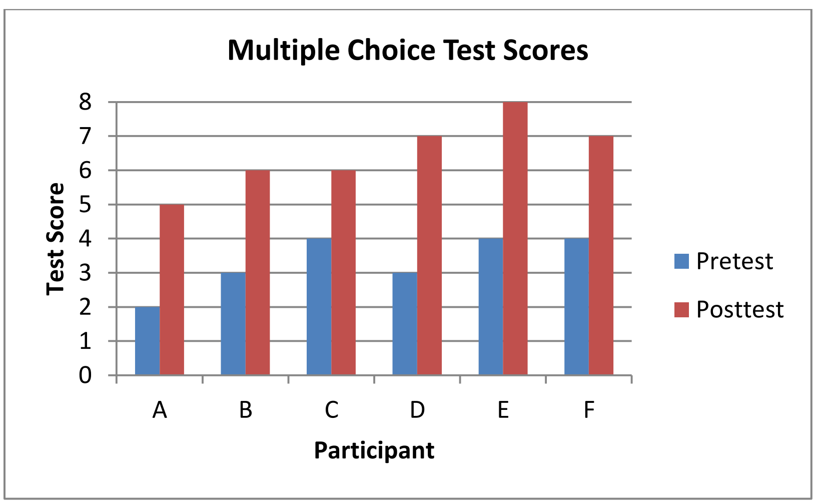


Figure 39. Participant scores for the multiple choice test taken before and after the learning phase in the VE. A score of eight was the highest possible score.

Essays were scored according to a rubric that awarded points in four categories: high-level descriptions of causes, details, logical explanation of cause and effect, and explanation of responsibility. Points were awarded in the high-level descriptions category (17 points possible) and the details category (45 points possible) based on the inclusion of specific events, factors, and details about those factors in the essay. The other two categories, explanation of causes and effects and explanation of responsibility were more subjective. To earn points for explanation of causes and effects, participants needed to clearly present a logical flow of factors leading up to the war, as included in the VE's data set. A maximum of 10 points was possible in this category. To earn points for the explanation of responsibility, participants had to argue a position for which country or countries were responsible for the war. Ten points were possible for this category, with points assigned based on the assertion of the position and the quality of its justification.

The purpose of the essay was to provide participants with a goal and provide a task to elicit recall of the information and environment. Still, essays were scored by a single reviewer from the research team to help gauge a general sense of participant comprehension. The scoring criteria are included in appendix F. Figure 40 shows these scores as percentages. We note that the percentages are generally low values due to the large number of possible points in the scoring rubric, the limited time of the learning exercise, and the lack of motivation for participants to both memorize and analyze the information. These results show that participants did pick up on a large portion of the high-level causes, but they did not report many specific details in their essays. The scores for the explanations of responsibility and cause-and-effect varied greatly.

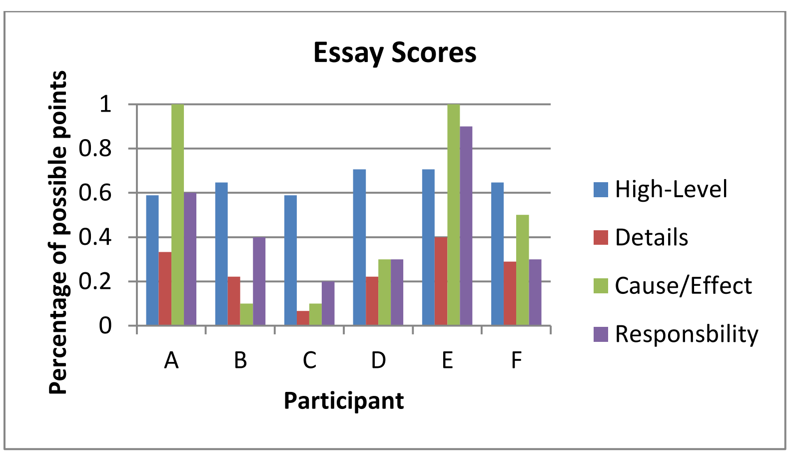


Figure 40. Participant scores for written accounts of the causes of the First World War.

8.8 Strategies and Viewing Approaches

Information on user strategies and viewing approaches was collected through observations during the learning activity and interviews after participants wrote their essays. Half of the participants chose to focus on the map area at the beginning of the exercise, while half staying in the main area at the start. In the main area, most participants moved through the information in the VE linearly, moving along the perimeter of the layout. Four of the six participants reported that they spent the most time on the timeline information than anything else. The other two participants gave preference to information about alliances and the assassination of the Archduke Ferdinand. Aside from these focal areas, there was relatively little re-visiting or re-reviewing information locations.

We also note that participants did find the elevated viewpoint useful for the map area, but only one participant used it frequently in the main area. This shows two things: 1) that the open layout of the main area made it easy to travel directly to locations, and 2) most participants did not feel the need to zoom out and view the layout from a different vantage point. This was not the case in the map area. All participants used the elevated viewpoint to study the map, as this provided a clear view and easy access to information on any of the major countries.

All participants reported that travel was easy and mindless. They also agreed that it was easy to tell where to go due to the large textual labels above each information group. Participants did not find the group images particularly helpful, and participants did not pay attention to them.

8.8.1 Sickness Results

Overall, results of the Simulator Sickness Questionnaire (R. S. Kennedy et al., 1993) showed low sickness effects. None of the three participants using the desktop application reported any symptoms (all total SSQ scores were 0.0). Participants using the VisCube version reported several symptoms as “slight” and one participant reported “moderate” fatigue (total SSQ scores were 260.24, 165.45, and 348.27). Note that these scores were very low, as the highest possible total SSQ score is 2437.88.

8.9 Conclusions of Case Study

The COWWI application provided a realistic learning scenario for a case study in design and development of an educational VE. We implemented the application for both an immersive VisCube display and for simple laptop use, and we conducted a small usability study to assess our design choices and learn more about the use of spatial information presentations. The study did not reveal any major problems with the design, but it did help to strengthen the design principles that evolved into the guidelines. The next chapter further discusses specific designs decisions and outcomes from the COWWI case study that helped to inform recommendations for design.

9 Design Guidelines for Spatial Information Presentations

From the results of our previous studies and the work of others, we have created a set of design guidelines for using spatial information presentations to support learning activities. In this section, we explain our recommendations and the study results from which they were derived.

9.1 Whether or not to use spatial presentations

The first issue when considering the use of a spatial information presentation is whether it will be appropriate and beneficial for the task. The results of Experiment I and other memorization studies (Hess, Detweiler, & Ellis, 1994; Hess et al., 1999) do support the claim that mapping information to locations can improve performance for cognitive tasks, but Experiment II with the puzzle activities shows that these mappings do not necessarily always yield benefits (at least not detectable benefits) for any task. Further, the results of our study using cartoon story cards (Experiment III) suggest that greater memory of locations is not in itself enough to improve understanding. Yet the results from several of our studies show that many people (but not all) did refer back to locations, the layout, or the environment when thinking about informational content (Experiments I, III, IV, and V).

So what does this mean about the decision for whether to use spatial presentations? The theories of spatial indexing and contextual memory do support the idea that that mapping information to locations can support meaningful recall, but our empirical evidence shows that this is not always the case. The use of space is not a silver bullet that will automatically yield benefits. The real benefits of using educational VEs probably do not stem from the use of spatial presentations alone, but from combining locations and context with other attributes and outcomes of the applications (e.g., interactivity, engagement, active learning, and opportunities for collaborative learning). Effectively using space is complicated and probably not worth attempting without an investment in some time designing the layout. The more complex the task and information are, the more decisions must be made for a meaningful layout.

9.2 Spatial layout

How should the information locations be distributed in the VE? There is certainly not a single correct method for laying out information in space, but we have learned enough to make several recommendations to help guide this decision.

9.2.1 Meaningful organization

Our results have suggested that spatial presentations are more useful when the spatial organizations have meaningful mappings of information to locations (Experiment I), and random distributions can be troublesome for learners (Experiment III). If there is an inherent or existing meaningful organization that fits the task and data set, then it should of course be used in the layout design. If multiple logical organizations exist, we suggest referring back to the learning objectives for the task, and picking the organization that best supports these goals. While this may seem obvious, complex learning activities can have many reasonable layouts, and it can be tempting to choose the one that groups the data most efficiently. However, the application should not merely be grouping information; it should help the user to achieve the learning objectives.

We encountered this issue in designing the COWWI application. Possible meaningful layouts included strictly geographic and strictly chronological organizations. These options were relatively straightforward and convenient organizations. While we considered these options and do not think that they would have necessarily been poor choices, the primary purpose of the application was to help learners to understand the many different causes of the war. Neither the geographic or temporal layouts clearly organized the different events and sources of tension leading to WWI. As a result, we chose to design a layout that emphasized the many causes. Additionally, in an effort to still provide some organization based on the geographic and temporal structuring, we included a timeline presentation and a secondary spatial layout of country information organized on map.

9.2.2 Reducing search

For users to be able to easily use the spatial organization to assist their own learning, it should be easy to find information items. This is important for viewing information for the first time (so it is not missed) and to find items that were previously viewed (to reanalyze or reinforce the information). The layout should be designed in a way that reduces the amount of search that users need to do. One way to do this is by maximizing the number of items/locations that are visible from any given location, and by providing clear lines of sight with open areas or zoomed-out views. Grouping or hierarchical structuring can also help to facilitate information access and reduce search time. In addition, textual labels, imagery, or other types of indicators can help make it easy to recognize a location's content from a distance.

These recommendations are based on the development and user testing of the COWWI application, as well as from observations with the animal facts VE (Experiment IV) and the data exploration VE (Experiment V). Search in itself could be problematic, particularly for users with little video game experience who struggled with travel and navigation in the virtual space. In the COWWI environment, the majority of the information was roughly configured in a large horseshoe shape (shown in the right half of Figure 35) for high visibility of all information. Information was organized into small groups based on major events or sources of tension that contributed to starting WWI. Additionally, an elevated viewpoint made it possible to see many groups at once from a zoomed-out perspective. Groups were labeled with textual labels and marked with image textures related to group themes. In the map area of the environment (shown on the left side of Figure 35), information was organized roughly around the countries on the map, but were spread out to limit occlusion. As with the causation horseshoe, the entire map area was visible from an elevated viewpoint above the map. The small groups in the map area were also labeled with large textual headers.

9.2.3 Layout complexity

A 3D VE had three dimensions in which it is possible to layout information, but this does not mean that it is necessary or beneficial to distribute information in all possible dimensions. Experiment III showed that increasing the spatial distribution did increase the memory of where information was, but it also negatively affected learning outcomes when it was difficult to access that information. We recommend limiting the complexity of a layout as far as is reasonable for the organization scheme. On the other hand, an overly simplified layout (e.g., listing all items in a straight line) may not be much help for large data sets or complex tasks. In our study with the animal facts task (Experiment IV), participant feedback indicated that straight lines were not helpful due to their symmetry and lack of spatial variance. We think that logical information grouping decisions can help to balance the benefits and challenges associated with increased layout complexity.

9.3 Information grouping

Grouping small numbers of items within simple layouts can limit the layout complexity within groups while still allowing more spatial distribution among groups. More work is needed to better understand appropriate groups sizes for spatial information presentations. From Experiment IV, we saw that five items in a group may be too many if the items are not clearly related, but user tests with the COWWI environment found that five may be an appropriate size for groups of related items. We also know relatively little about the number of groups that users can keep straight during cognitive activities. When asked about the groups in COWWI, with its 15 distinct information locations, participants did not report any problems with the number of groups/locations. Participants agreed that group labels made it easy to keep track of groups and that the number of items was not overwhelming during the learning activity, though memory of information locations after the activity was quite poor. This suggests that users might have trouble referring back to specifics of a layout with large groups to aid in recall, but more research is needed to test this hypothesis. Experiment III, with a 2D distribution of cartoon images, found that participants remembered around eight locations on average, but individual variance was high (M = 8.31, SD = 4.02).

9.4 Supplemental environmental detail

Supplementing information locations with additional imagery can affect perception of the location's context. Additional visuals can also serve as landmarks to make locations more easily recognizable or memorable. In the study in which we compared information presentations either with or without the addition of simple models and textures (Experiment IV), the results did not show significant differences in learning outcomes. Interviews with participants found that users had different opinions regarding landmarks and supplemental imagery. Some people found all extraneous imagery to be distracting, yet others found a lack of detail in an application to be troubling or depressing. For others, it was helpful to have related environmental detail, but whether they thought the details were related depended on individual preference and the ability to connect it to the information. For some people, even unrelated landmarks helped make locations more memorable.

As a result, we recommend adding related detail, but limiting the amount of supplemental visual detail to reduce possible distractions. While environmental detail may not provide advantages for everyone, it may make the activity more memorable for some users, and choosing simple and related items will reduce the chances of distracting learners. In the COWWI application, we added 2D images to information groups. For some groups, the group topic afforded easy choices for related imagery. For example, we added a picture of a clock to the location showing a timeline of events, and we added a picture of soldiers to the location with information about the arms buildup. For locations where the information did not lend itself to a simple and memorable related visual, we instead chose images that we thought might symbolize the relevance of the content to the learning activity. For example, we added a picture of handshake to the information group about alliances among countries, and we added a picture of a cartoon fight cloud to a group about when Austria-Hungary annexed Bosnia-Herzegovina. While these visuals may not be uncontested ideal choices, we hoped that they would be simple and memorable.

From our post-session interviews about COWWI, we found that participants did pay much attention to the supplemental landmark visuals. None of the users reported that the visuals were distracting, and none reported that they were especially helpful. Participant memory of the images was low (most participants only remembered one or two images). All users indicated that they used only the textual labels as landmark references, and they did not knowingly use the images.

9.5 Travel and view control

Movement in 3D environments can be complicated, and many travel techniques have been used for various applications. Travel and view control should be easy and mindless. Learners should be able to focus on the educational activity, rather than spending attentional resources thinking about how to adjust the view or trying to comprehend unexpected viewing changes.

9.5.1 Consider automated travel

Complete manual control over travel and viewing provides users with the ability to precisely adjust the virtual camera. While a greater degree of control may be beneficial for some tasks and VEs (as seen in Experiment V), it also gives users more to worry about during a learning exercise. For some learning activities, such as the animal facts task and the cartoon story task from our studies, having additional control may not even provide noticeable benefits (as seen in Experiments III and IV). In both of these studies, the analyses did not detect significant differences between automated and interactive travel methods for learning outcomes. If it is not believed that a learner will benefit from interactive control, it may be a better option to automate viewing.

For activities that require interactive travel, as might be found in applications promoting exploration or decision making, we recommend limiting and simplifying the level of interactive control. Many applications do not require users to have complete control of movement in every possible degree of freedom. In many VEs, for example, it is already common to disallow controlling camera roll. Further, because educational environments often have specific focal points, it may make sense to support automatic view transitions to these points, which could eliminate the need to manually control all degrees of freedom. Automating some degrees of freedom in travel can simplify interaction without sacrificing user control over the order and duration of information viewing.

In our data exploration application (Experiment V), we compared manual steering travel (via standard flying with a tracked wand controller) to a simplified target-based travel technique. With the target-based technique, participants could control heading rotation and select target locations to which they would automatically move. For data exploration, manual steering did provide better performance for one of the task types (identifying relationships between two data types), but steering also caused sickness and frustration (particularly for users without much video game experience). Additionally, with manual steering in the animal facts VE (Experiment IV), we observed that many users were wasting their time and attention trying to line up specific information items with the screen.

We designed the COWWI application to avoid these problems. At each information location, information cards were arranged in a semi-circular layout. This way, the learner could view the items in the group by staying in the center of the arrangement and rotating in place. To travel to other groups, learners used ray-casting to select another group, and would then automatically transition to that location. This seemed to work very well. When asked about problems and difficulties with travel, no participants reported negative issues, and all stated that they could travel easily and could look at what they wanted to without having to think about it.

9.5.2 Limit collisions

From participants using manual steering in the data exploration environment (Experiment V), as well as from our observations and testing with other applications, we know that many users do not like traveling through virtual geometry. While this may be obvious for many practitioners of VR, it is important to remember to limit collisions with geometry when designing an information layout.

The most direct path for travel might not be the best path if it unexpectedly moves the user through a wall. This recommendation overlaps with the previously mentioned points about layout complexity and search reduction. Open spaces and clear sight makes it easier to perceive a layout and to find items of interest.

9.6 Display and interaction factors

The results of many previous studies provides evidence that high-fidelity VR systems can be beneficial for tasks in spatial contexts, which of course include spatial information presentations. Still, it is important to consider that adding enhanced display features could potentially introduce problems with sickness and discomfort. Of course, many of these effects depend on individual differences, and it can be difficult to predict whether a user will benefit from display features or experience adverse effects.

9.6.1 Support natural physical viewing

Numerous previous studies have contributed evidence that higher fidelity display and interaction components can affect navigation and understanding of spatial layout (e.g., Chance et al., 1998; Ruddle et al., 1999). Many studies concluded that natural, high-fidelity view control is a major factor providing benefits for spatial tasks (e.g., Chance et al., 1998; Ragan, Kopper, Schuchardt, & Bowman, 2012; Ruddle et al., 1999; Tan et al., 2004). In one notable example, Zanbaka et al. (2004) evaluated performance on a task involving the recollection, comprehension, and synthesis of information about items distributed throughout a VE. The study compared travel techniques and found that real physical walking provided better outcomes than the other travel techniques (such as joystick navigation). In our previous research, we evaluated recall time and accuracy on a memorization task involving the sequential placement of colored, geometric solids in specific locations (Ragan et al., 2010). This study found that the greatest performance improvements were attributed to increased field of regard, which allowed the use of physical rotation to view the VE due to surrounding screens. While these previous studies did not specifically focus on spatial information presentations, they are certainly highly relevant, as they consider navigation, cognition, and spatially distributed objects. The resulting evidence from these studies supports the recommendation for allowing natural (higher-fidelity) travel and viewing. Allowing the use of surrounding displays, large screens, and real walking (when possible) are straightforward interpretations of this guideline.

9.6.2 Limit visual clutter

Despite the potential benefits, the results of our studies do not justify the claim that higher fidelity display features always yield positive results. In the data exploration VE (Experiment V), we found that the higher fidelity conditions (with the addition of stereo, head tracking, and increased field of regard) caused sickness and discomfort. We concluded that the sickness was the cause for the significant performance drops associated with the same conditions. We think that the adverse effects can be partially attributed to the overwhelming amount of visual stimuli in the VE. The higher level of visual fidelity increased the amount of perceived stimuli. Additionally, the high-fidelity visualization still has imperfect cues (e.g., mismatch between ocular accommodation and convergence, use of the same preset pupillary distance for all users, and color filtering from passive stereo), and we suspect that these problems were amplified by the overwhelming amount of visual content. As a result, we recommend limiting the amount of visual clutter and contrast in spatial information presentations, particularly with high-fidelity display systems.

9.6.3 Limit elevation changes

Another notable problem observed in the data exploration VE was elevation changes. Participants reported that moving up and down in the virtual cave was particularly troubling, and we noted that the addition of the floor screen made these movements more jarring for participants in the high fidelity conditions. While the presence of the ground screen did allow users to view more of the VE and use physical body movements to view information, the added discomfort may not have been worth these benefits. Similarly, in the evaluation of the COWWI application, one participant in the VisCube version did comment on discomfort with changing elevation when moving to and from the elevated viewpoints. As a result of these two studies, we recommend limiting vertical movements for displays with a large vertical field of regard (i.e., those that allow participants to physically look up and down to view the VE).

9.7 Summary of design guidelines

For convenience, the design guidelines discussed in this chapter are summarized in Table 9.

Issue	Description	Supporting Studies
Whether or not to use spatial presentations	Not guaranteed improvements, but in some cases can help improve recall.	(Hess et al., 1994, 1999; Ragan, Bowman, et al., 2012) Experiments I and II
	Probably not worth doing without spending time designing the layout. The more complex the task and information is, the more decisions must be made for a meaningful layout.	(Ragan, Bowman, et al., 2012; Ragan, Endert, et al., 2012) Experiments I, II, and III; Case study
Spatial layout	If there is a meaningful organization for the layout, use it. If multiple possible meaningful organizations, try to pick the one that is better for the focus of the learning objectives.	(Ragan, Bowman, et al., 2012; Ragan, Huber, et al., 2012) Experiments I and IV; Case study
	Try to reduce searching. Maximize the number of items/locations visible from any given location. Provide clear lines of sight with open areas or zoomed-out views.	(Ragan, Wood, et al., 2012) Experiment V; Case study
	Try to limit the complexity of a layout, but be aware that a layout that is overly simplified (e.g., listing all items in a straight light) might not be much help for large or complex tasks	(Ragan, Endert, et al., 2012; Ragan, Huber, et al., 2012) Experiments III and IV; Case study
Information grouping	Grouping small numbers of items within simple layouts can limit the complexity within groups while still allowing more spatial distribution among groups.	(Ragan, Huber, et al., 2012) Experiment IV; Case study
	Five items in a group may be too many if the items are not clearly related, but five may be an appropriate group size for related items. More work is needed to better understand appropriate groups sizes for spatial information presentations.	(Ragan, Endert, et al., 2012; Ragan, Huber, et al., 2012) Experiments III and IV; Case study
Supplemental environmental detail	People can have different opinions regarding landmarks and supplemental imagery.	(Ragan, Huber, et al., 2012) Experiment IV; Case study
	It can be helpful to have related environmental detail, but it depends on the learner's ability to connect it to the information. For some people, even unrelated landmarks may help if it is memorable.	(Ragan, Huber, et al., 2012) Experiment IV
	Some people find all extraneous imagery to be distracting, yet others could find a lack of detail in an application to be distracting or depressing.	(Ragan, Huber, et al., 2012) Experiment IV

Travel and view control	Simplify travel and the level of user control. For layouts that do require movement in more degrees of freedom, automate control over movements that do not affect the order or duration of information access, when possible	(Ragan, Endert, et al., 2012; Ragan, Huber, et al., 2012; Ragan, Wood, et al., 2012) Experiments III, IV, and V; Case study
	Limit collisions with virtual geometry	(Ragan, Wood, et al., 2012) Experiment V
	Limit vertical movements in immersive VEs.	(Ragan, Wood, et al., 2012) Experiment V; Case study
Display and interaction fidelity	Support natural physical viewing through surrounding displays, large screens, and physical walking	(Ragan et al., 2010; Zanbaka et al., 2004)
	Limit visual clutter with high fidelity displays	(Ragan, Wood, et al., 2012) Experiment V
	Limit elevation changes (particularly with high vertical field of regard)	(Ragan, Wood, et al., 2012) Experiment V; Case study

Table 9. Summary of design guidelines for the use of spatial information presentations to support learning and sense-making activities.

10 Conclusions and Future Work

10.1 Overview

The research presented in this dissertation focuses on supporting learning and information processing with spatial information presentations—visualizations that map information items to locations. As such, this work is highly relevant to educational 3D VEs due to availability of a potentially limitless amount of space in which to organize information. The goal has been to improve the design of spatial presentations by studying how learning outcomes and strategies are affected by software, interaction, and display factors. Based on data collected from five empirical studies and a case study with an educational application, we have refined design guidelines for the use of spatial information presentations to support learning and sense-making activities. The guidelines (presented in Chapter 9 and summarized in Table 9) include considerations for travel, information grouping, visual landmarks, information layout, and choice of display.

10.2 Summary of Findings

This section summarizes the research findings with regard to the research questions that were presented and explained in section 1.3.

Q1) How do spatial information presentations in virtual environments affect learning?

The results of Experiment I and other memorization studies (Hess et al., 1994, 1999) do support the claim that mapping information to locations can improve performance for cognitive tasks, but Experiment II with the puzzle activities shows that these mappings do not necessarily always yield benefits (at least not detectable benefits) for any task. Further, the results of our study using cartoon story cards (Experiment III) suggest that greater memory of locations is not in itself enough to improve understanding. Yet the results from several of our studies show that many people (but not all) did refer back to locations, the layout, or the environment when thinking about informational content (Experiments I, III, IV, and V). So, while the theories of spatial indexing and contextual memory do support the idea that that mapping information to locations can support meaningful recall, our empirical evidence shows that this is not always the case. Spatial distribution is not a simple means of automatically improving learning, and other factors (e.g., organization, view control, environmental detail) can certainly influence the way that locations and spatial mappings are perceived.

Q2) How does spatial layout complexity affect learning using spatial presentations in virtual environments?

A 3D VE has three dimensions in which it is possible to present information, but this does not mean that it is necessary or beneficial to distribute information among all possible dimensions. Experiment III showed that increasing the spatial distribution did increase the memory of where information was, but it also negatively affected learning outcomes when it was difficult to access that information. On the other hand, an overly simplified layout (e.g., listing all items in a straight line) may not be much help. In the study with the animal facts task (Experiment IV), participant feedback indicated that straight-line groupings were not helpful due to their symmetry and lack of spatial variance. Though focused investigation of the effects of different grouping or organization schemes was beyond the scope of our primary research objectives, it is difficult to separate layout from organization in practical applications. Further research is needed to investigate whether logical information grouping decisions can help to balance the benefits and challenges associated with increased layout complexity.

Q3) Do the effects of spatial information presentations on learning depend on the spatial fidelity of the system?

Many studies concluded that natural, high-fidelity view control is a major factor providing benefits for spatial tasks (e.g., Chance et al., 1998; Ragan, Kopper, et al., 2012; Ruddle et al., 1999). Despite the potential benefits, the results of our studies do not justify the claim that higher fidelity display features always yield positive results. In the data exploration VE (Experiment V), we found that the higher fidelity conditions (with the addition of stereo, head tracking, and increased field of regard) caused sickness and discomfort. We concluded that the sickness was the cause for the significant performance drops associated with the same conditions. Another notable problem observed in the data exploration VE was elevation changes. Participants reported that moving up and down in the virtual cave was particularly troubling, and we noted that the addition of the floor screen made these movements more jarring for participants in the high-fidelity conditions. While the presence of the ground screen did allow users to view more of the VE and use physical body movements to view information, the added discomfort may not have been worth these benefits. Similarly, the user study with the COWWI application provided evidence of participant discomfort with changing elevation.

From the results of our studies in combination with prior studies (e.g., Zanbaka et al., 2004), we can say that spatial fidelity can affect cognitive activities involving spatial information presentation. However, increasing spatial fidelity does not always result in positive effects. Our research has shown that the observed effects may be difficult to predict. We could learn more from additional studies that analyze types of movements in conjunction with spatial distribution and interaction methods.

Q4) How does the level of user control in viewing information layouts affect learning?

While a greater degree of control may be beneficial for some tasks and VEs (as seen in Experiment V), it also gives users more to worry about during a learning exercise. For some learning activities, such as the cartoon story task (Experiment III) and the animal facts task (Experiment IV), having additional control may not even provide noticeable benefits. In both of these studies, the analyses did not detect significant differences between automated and interactive travel methods for learning outcomes. Additionally, with manual steering in the animal facts VE (Experiment IV), we observed that many users were wasting their time and attention trying to line up specific information items with the screen. In Experiment V, manual steering did provide better performance for one of the task types (identifying relationships between two data types) when compared to a partially-automated travel technique. However, the manual steering also caused sickness and frustration (particularly for users without much video game experience). Based on all of these results, we conclude that it may be a better option to automate viewing when possible during learning activities (so long as it is not expected that a learner will need or benefit from interactive decision making).

Q5) How do landmarks and environmental detail affect learning with spatial information presentations?

We expected that adding visual imagery to information locations would make locations more memorable, and thus improve learning outcomes in spatial contexts. However, the results of our studies cannot confirm this hypothesis. Though the results of Experiment I do suggest that visual imagery significantly affected memorization strategies, there was no evidence of differences in learning outcomes. Experiment IV compared information locations with or without accompanying models and textures, and again no differences were detected. Interviews with participants after Experiment IV suggest that users had different opinions regarding landmarks and supplemental imagery. Some people found all extraneous imagery to be distracting, yet others found a lack of detail in an application to be troubling or depressing. For others, it was helpful to have environmental detail related to the information at that location, but whether they thought the details were related depended on individual preference and the ability to connect it to the information. For some people, even unrelated landmarks helped make locations more memorable. From our interviews after the COWWI user studies, we found that participants did not pay much attention to the supplemental landmark visuals. None of the users reported that the visuals were distracting, and none reported that they were especially helpful. The variety of opinions and usage strategies suggest that any effects of selected environmental detail depend highly on individual preferences.

10.3 Summary of Contributions

1) We provide a description of the problem space to help organize the research space for learning-based 3D environments. This will allow other researchers to see how this work fits into the existing body of research in educational VEs and reveal what areas could most benefit from further investigation.

2) We add to the conceptual and scientific understanding of the role of space and navigation for learning activities through empirical evidence collected from five experiments, contributing to the disciplines of psychology, education, and human-computer interaction. Our results and analyses provide further insight into: (a) the effects of display and software

factors on performance in cognitive processing activities, and (b) the strategies employed by users in cognitive processing activities. Though this body of research is presented within the context on educational VEs, spatial information presentations are also relevant to a variety of other information presentation formats (e.g., museum exhibits, visual analytics tools, or presentation software). Many of the scientific findings reported within this dissertation can be applied to other domains.

3) We provide design guidelines for developing spatial information presentations. These guidelines are based on empirically-gathered evidence and refined through their application to the development of a real application. The generated guidelines include considerations for: (a) the design of the virtual world, based on the concepts of spatial layout complexity and degree of interactive control, and (b) properties of the display systems used for the VEs, based on the analysis of the effects of spatial fidelity.

10.4 Future Work

This research has contributed to a greater understanding of how design decisions affect outcomes and strategies in cognitive tasks, but this is a small set of studies. Replication of these experiments is important to validate (or refute) the observed findings and increase (or decrease) the strength of the claims made in this dissertation. Further, our results do not provide a definitive set of outcomes for the design factors that we focused on (i.e., environmental detail, level of control, spatial fidelity, and layout complexity). Additional studies are needed for a more complete understanding of how these design factors influence learning with spatial information presentations.

Unanswered questions remain about the use of locations and the usefulness of context during learning activities. The use of space is only one of many properties of VEs that has potential benefits for learning. By combining spatial and contextual presentations and with other potentially beneficial attributes of educational VEs (e.g., interactivity, engagement, active discovery scenarios, and opportunities for collaborative learning), it is possible to derive a more complete set of design guidelines. In addition, a number of design issues remain about how to integrate design guidelines for the use of space within complete educational applications, such as educational games. For example, future research of the roles of narrative or motivational elements in educational games could be combined with research of spatial information presentations or the memory of locations.

Integration of these components is important for creating meaningful and memorable learning experiences, and experimentation and evaluation can help to provide a more structured analysis of design effectiveness for complex educational software.

Further, aside from purely virtual environments, future studies of spatial information presentations can continue not just in individual virtual spaces, but also in distributed workspaces—it would be interesting to study how the perception of locations and spatial mappings are affected by visualizations that are split among multiple frames of reference on separate displays or devices. It could also be interesting to study shared perceptions of space with displays and systems that can accommodate multiple simultaneous users.

Lastly, while this dissertation is presented within an organizational framework focusing on educational VEs (see Chapter 3), spatial information presentations are relevant to a variety of types of information presentation or exploration—including museum exhibits, visual analytics tools, and presentation software, as a few examples. Many of the findings reported within this body of work are relevant to other applications, and it would also be interesting to study the same (or analogous) design factors in the context of other domains.

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Appendix A: Experiment Documents for Experiment I

VirginiaTech

Office of Research Compliance
Institutional Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24061
540/231-4991 Fax 540/231-0959
e-mail moored@vt.edu
www.irb.vt.edu
FWA00000572(expires 1/20/2010)
IRB # is IRB00000667

DATE: March 10, 2009

MEMORANDUM

TO: Doug A. Bowman
Eric Ragan

Approval date: 3/10/2009
Continuing Review Due Date:2/23/2010
Expiration Date: 3/9/2010

FROM: David M. Moore

SUBJECT: **IRB Expedited Approval:** "Supporting Procedure Memorization through Spatial Presentation" , IRB # 09-231

This memo is regarding the above-mentioned protocol. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective March 10, 2009.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.
3. Report promptly to the IRB of the study's closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher's responsibility to obtain re-approval from the IRB before the study's expiration date.
4. If re-approval is not obtained (unless the study has been reported to the IRB as closed) prior to the expiration date, all activities involving human subjects and data analysis must cease immediately, except where necessary to eliminate apparent immediate hazards to the subjects.

<u>**Important:**</u>
If you are conducting **federally funded non-exempt research**, please send the applicable OSP/grant proposal to the IRB office, once available. OSP funds may not be released until the IRB has compared and found consistent the proposal and related IRB applicaton.

cc: File

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

An equal opportunity, affirmative action institution

Informed Consent for Participant of Investigative Project

Virginia Polytechnic Institute and State University

Title of Project: Supporting Procedure Memorization through Spatial Presentation

Principal Investigators: Dr. Doug A. Bowman, Eric Ragan

11 I. THE PURPOSE OF THIS RESEARCH/PROJECT

The purpose of this study is to achieve greater knowledge of what design features of immersive virtual reality (VR) systems support different levels of cognitive processing through investigation of recall performance for a procedural memorization task. Such knowledge is important in order to understand how to design software applications that effectively support learning.

II. PROCEDURES

You will be asked to perform a set of tasks using a virtual environment system. These tasks consist of navigating through a 3D environment or manipulating virtual 3D objects. You will wear stereoscopic glasses while using the CAVE™. Your role in these tests is that of evaluator of the software. We are not evaluating you or your performance in any way; you are helping us to evaluate our system. All information that you help us attain will remain anonymous. The time you take to do each task and other aspects of your interaction with the system will be measured. You may be asked questions during and after the evaluation, in order to clarify our understanding of your evaluation.

You may also be asked to fill out a questionnaire relating to your background with such systems, and to take a short test of spatial ability.

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

You will be given full instructions before every task. Because we are measuring a range of abilities, some tasks will be easy and others difficult. It is important that you understand the instructions before beginning each task. If anything is unclear, be sure to ask us questions.

III. RISKS

The proposed experiments are straightforward tests of performance using standard virtual environments displays, trackers, and input devices. Participation involves sitting in a chair within the CAVE and performing simple memorization tasks. The physical components of these tasks are not stressful, and include head and body turning. All light and sound intensities are well within normal ranges. The only foreseeable physical risks are slight eye strain, dizziness, or mild nausea. The potential mental risks are mental strain or fatigue due to the cognitive demand of memorization.

You are encouraged to take breaks and relax between trials in order to minimize these risks. If you experience any eye strain, dizziness, or nausea during a session, please step away from the CAVE and take a rest break. If you feel any discomfort during any task, please tell us. If dizziness, nausea, or mental stress becomes uncomfortable, you will be allowed to leave with no penalty.

IV. BENEFITS OF THIS PROJECT

Your participation in this project will provide information that may be used to improve the design of virtual environments software meant to support training or learning-based activities. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed. Please leave a self-addressed envelope with the experimenter and a copy of the results will be sent to you.

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

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

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

VI. COMPENSATION

Your participation is voluntary and unpaid.

VII. FREEDOM TO WITHDRAW

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

VIII. APPROVAL OF RESEARCH

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

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

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

____ ________
Signature Current Date

____ ____________
Name (please print) Date of Birth

____
Contact: phone or address or email address (OPTIONAL)

Should I have any questions about this research or its conduct, I may contact:

Investigator: Dr. Doug A. Bowman Phone (540) 231-2058
Professor, Computer Science Department (231-6931)
email: bowman@vt.edu

Eric Ragan Phone (814) 431-4576
Graduate Student, Computer Science Department (231-6931)
email: eragan@vt.edu

User Questionnaire

Please help us to categorize our user population by completing the following items.

Gender (circle one): Male Female

Age: _____________

Do you wear glasses or contact lenses (circle one)?
No Glasses Contact Lenses

Are you color blind (circle one)?
No Yes Not Sure

Occupation (if student, indicate graduate or undergraduate): ____________________________

Major / Area of specialization (if student): _________________________________

Rate your experience with video games: (circle one)

•-----------------------•-----------------------•-----------------------•-----------------------•
not at all not very somewhat fairly very experienced

How often do you play video games:

•-----------------------•-----------------------•-----------------------•-----------------------•
never or almost never ever few months monthly weekly daily

Have you ever used a virtual reality (VR) or augmented reality (AR) system? If so, please describe it (what type of display was used, what kind of application (e.g. game, architectural walk-through) was running, how did you interact with the system, etc.).

Appendix B: Experiment Documents for Experiment II

VirginiaTech

Office of Research Compliance
Institutional Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24061
540/231-4991 Fax 540/231-0959
e-mail moored@vt.edu
www.irb.vt.edu
FWA00000572(expires 1/20/2010)
IRB # is IRB00000667

DATE: October 2, 2009

MEMORANDUM

TO: Doug A. Bowman
Eric Ragan
Tonya L. Smith-Jackson

FROM: David M. Moore

Approval date: 10/2/2009
Continuing Review Due Date:9/17/2010
Expiration Date: 10/1/2010

SUBJECT: **IRB Expedited Approval:** "Supporting Cognitive Processing with Spatial Information Presentations in Virtual Environments" , IRB # 09-808

This memo is regarding the above-mentioned protocol. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective October 2, 2009.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.
3. Report promptly to the IRB of the study's closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher's responsibility to obtain re-approval from the IRB before the study's expiration date.
4. If re-approval is not obtained (unless the study has been reported to the IRB as closed) prior to the expiration date, all activities involving human subjects and data analysis must cease immediately, except where necessary to eliminate apparent immediate hazards to the subjects.

Important:
If you are conducting **federally funded non-exempt research**, please send the applicable OSP/grant proposal to the IRB office, once available. OSP funds may not be released until the IRB has compared and found consistent the proposal and related IRB applicaton.

cc: File

Informed Consent for Participant of Investigative Project

Virginia Polytechnic Institute and State University

Title of Project: Supporting Cognitive Processing with Spatial Information Presentations in Virtual Environments

Investigators: Dr. Doug A. Bowman, Eric Ragan, Dr. Tonya Smith-Jackson

I. THE PURPOSE OF THIS RESEARCH/PROJECT

The purpose of this study is to achieve greater knowledge of what design features of immersive virtual reality (VR) systems support different levels of cognitive processing through investigation of problem solving performance using large display systems. Such knowledge is important in order to understand how to design software applications that effectively support learning.

II. PROCEDURES

Each trial will consist of a learning phase and a problem solving phase. In the learning phase, you will view a series of images in a CAVE™ virtual environment. These images will contain simple geometric objects that are arranged according a number of simple rules. Your task is to figure out the rules based on the images. The images will be displayed one at a time, each for a fixed amount of time. You will then be removed from the CAVE™ and asked to complete a brief paper exam after each trial. Your role in these tests is that of evaluator of the software. We are not evaluating you or your performance in any way; you are helping us to evaluate system design. All information that you help us attain will remain anonymous. The time you take to do each task and exam scores will be measured.

You may also be asked to fill out a questionnaire relating to your background with such systems, and to answer additional questions after completion of the experiment.

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

You will be given full instructions before every task. Because we are measuring a range of abilities, some tasks will be easy and others difficult. It is important that you understand the instructions before beginning each task. If anything is unclear, be sure to ask us questions.

III. RISKS

The proposed experiments are straightforward tests of performance using standard virtual environments displays. Participation involves sitting in a chair within the CAVE and performing a problem solving task. The physical components of these tasks are not stressful, and may include head and body turning. All light and sound intensities are well within normal ranges. The only foreseeable physical risks are slight eye strain, dizziness, or mild nausea due to the large display environment. The potential mental risks are mental strain or fatigue due to the cognitive demand of memorization.

You are encouraged to take breaks and relax between trials in order to minimize these risks. If you experience any eye strain, dizziness, or nausea during a session, please step away from the CAVE and take a rest break. If you feel any discomfort during any task, please tell us. If dizziness, nausea, or mental stress becomes uncomfortable, you will be allowed to leave with no penalty.

IV. BENEFITS OF THIS PROJECT

Your participation in this project will provide information that may be used to improve the design of virtual environments software meant to support training or learning-based activities. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed. Please leave a self-addressed envelope with the experimenter and a copy of the results will be sent to you.

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

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

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

VI. COMPENSATION

Your participation is voluntary and unpaid.

VII. FREEDOM TO WITHDRAW

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

VIII. APPROVAL OF RESEARCH

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

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

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

____ _______

Signature Current Date

____ _____________

Name (please print) Date of Birth

Should I have any questions about this research or its conduct, I may contact:

Investigator: Dr. Doug A. Bowman Phone (540) 231-2058
Professor, Computer Science Department (231-6931)
email: bowman@vt.edu

Eric Ragan Phone (814) 431-4576
Graduate Student, Computer Science Department (231-6931)
email: eragan@vt.edu

Dr. Tonya Smith-Jackson Phone (540) 231-4119
Professor, Industrial Systems & Engineering Department (231-6931)
email: smithjack@vt.edu

User Questionnaire

Please help us to categorize our user population by completing the following items.

Gender (circle one): Male Female

Age: _____________

Do you wear glasses or contact lenses (circle one)?
No Glasses Contact Lenses

Are you color blind (circle one)?
No Yes Not Sure

Occupation (if student, indicate graduate or undergraduate): ____________________________

Major / Area of specialization (if student): _________________________________

How often do you use computers?: (check one)

☐	☐	☐	☐	☐
never or almost never	ever few months	monthly	weekly	daily

Rate your experience with video games: (check one)

☐	☐	☐	☐	☐
none	low	somewhat	fairly high	very experienced

How often do you play video games?: (check one)

☐	☐	☐	☐	☐
never or almost never	ever few months	monthly	weekly	daily

Have you ever used a virtual reality (VR) or augmented reality (AR) system? If so, please briefly describe what type of display was used, what kind of application (e.g. game, architectural walk-through) was running, and how you interacted with the system.

Exit Interview

When viewing the images on the display, please explain the procedure or strategy you used to try to figure out the relationship between the symbols and the location of the circle:

Please explain your thought process when solving the problems:

Did you have any preference having the images displayed in the center screen or shown on multiple screens? Please explain why or why not.

Did you feel that any trials were easier or harder than the others? Please specify if you are able. If there were any differences, what do you think made the difference?

How strong do you feel your mathematical ability is?

(Weak) 1 ---- 2 ---- 3 ---- 4 ---- 5 ---- 6 ---- 7 ---- 8 ---- 9 ---- 10 (Strong)

How do you feel about completing puzzles?: (either for work or for fun)

☐	☐	☐	☐	☐
hate puzzles	do not care for puzzles	no strong feeling	sometimes fun	fun

Appendix C: Experiment Documents for Experiment III

VirginiaTech

Office of Research Compliance
Institutional Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24060
540/231-4606 Fax 540/231-0959
e-mail irb@vt.edu
Website: www.irb.vt.edu

MEMORANDUM

DATE: September 17, 2010

TO: Doug A. Bowman, Alexander Endert, Eric Ragan

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires June 13, 2011)

PROTOCOL TITLE: Effects of Interaction and Organization on Learning and Sensemaking

IRB NUMBER: 10-742

Effective September 17, 2010, the Virginia Tech IRB Chair, Dr. David M. Moore, approved the new protocol for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at http://www.irb.vt.edu/pages/responsibilities.htm (please review before the commencement of your research).

PROTOCOL INFORMATION:
Approved as: **Expedited, under 45 CFR 46.110 category(ies) 4, 6, 7**
Protocol Approval Date: **9/17/2010**
Protocol Expiration Date: **9/16/2011**
Continuing Review Due Date*: **9/2/2011**
*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:
Per federally regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals / work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

*Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

cc: File

Informed Consent for Participant of Investigative Project
Virginia Polytechnic Institute and State University

Title of Project: Effects of Interaction and Organization on Learning and Sensemaking

Principal Investigators: Dr. Doug Bowman, Dr. Francis Quek, Eric Ragan, Alex Endert

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study examining the cognitive effects of various levels of interaction and sizes of workspaces in which to organize information have on users' ability to understand, learn, and recall information. The results of this study will inform the development of future learning and analytic tools.

II. PROCEDURES

You will be asked to perform a short task where you will be presented with a collection of information that you will be asked to make sense of and remember.

The entire session will be video taped, and you may occasionally be interrupted and asked about your progress. Your movement, screenshots, eye-movement, and mouse movement will also be captured for further analysis.

III. RISKS

There is minimal risk involved with this study. If you experience headaches or other discomforts, please feel free to step back from the display and inform the experimenter.

IV. BENEFITS OF THIS PROJECT

Your participation in this project will provide information that may be used to inform the design of tools intended to aid users understand and learn information. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed. Please leave a self-addressed envelope with the experimenter and a copy of the results will be sent to you.

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

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. While a video and audio record will be made, only unique subject numbers will be used in analysis and reports.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason. You are free not to answer any questions you choose not to.

VIII. APPROVAL OF RESEARCH

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

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

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

Signature Date

Name (please print) Contact: phone or address or

email address (OPTIONAL)

Should I have any questions about this research or its conduct, I may contact:

Investigator: Alex Endert Phone (978) 314-7881
Graduate Student, Computer Science Department
email: aendert@cs.vt.edu

Review Board: David M. Moore, Office of Research Compliance
2000 Kraft Drive, Suite 2000, VA 24060 231-4991

cc: the participant, Alex Endert

Demographic Survey **Subject ID ________**

Gender (circle one): Male Female

Age: _______

Occupation (if student, indicate graduate or undergraduate):

____

Major / Area of specialization (if student): ______________________________

Describe any experience with large displays [gigapixel, storn, the table, multiple monitors, etc.]:

____

____

____

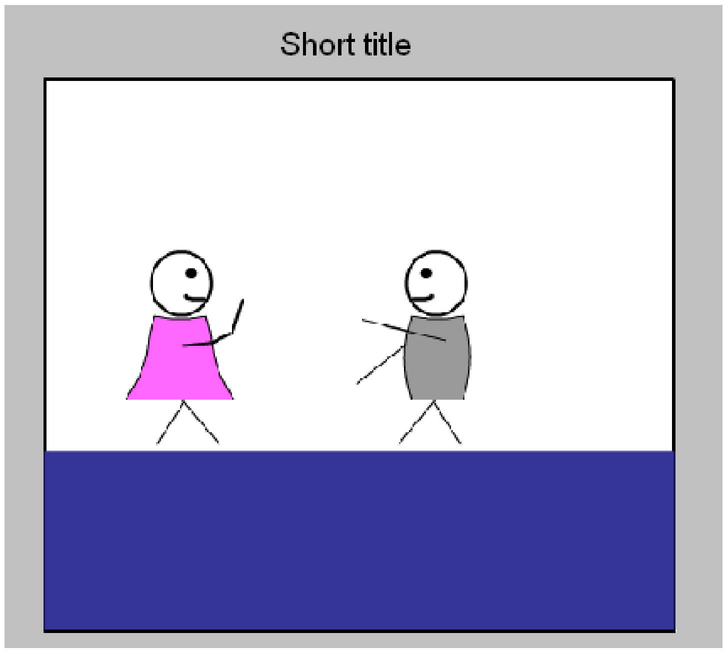
Do you regularly wear prescription contacts (circle one)? Yes No

Do you have any known color blindness (circle one)? Yes No

Description of Story Cards

You are going to see a number of different square cards. Each card has a graphical, cartoon representation of some event involving characters and objects. The top of each panel also has a short, textual title that corresponds to the event.

Example:



The collection of different cards makes up a set of stories that happen within the course of the same day. Characters can be distinguished from each other by clothing color, hair styles, and distinguishing objects that they have with them. Characters do not change clothes or hair styles throughout the story, so characters with different appearances are different people.

< Software introduction >

Your Task

Identify the story and sub-stories based on the events that you see. Pay attention to how the characters are connected to each other in the stories. You are to assume that all the events happen within the same day. After viewing the event cards, we will ask you questions about the stories, including questions about details and explanations for individual events.

You should also try to learn the titles of the cards. We are going to ask you to remember the names of the events. Additionally, when we ask you about the stories, we will refer to the events by the titles of the cards.

The order or organization of the event cards does not determine the sequence in which the events happen in the story; it will be your task to make sense of the events in any way you think is appropriate.

Number Span Memory Test

I am now going to ask you take a quick auditory number span test. For this test, I will call out a sequence of numbers. After I finish reading the numbers, please write down the numbers in the exact that they were read. Please do not write any numbers until I have finished reading the whole sequence.

When writing down the numbers, please try to leave blank spaces for any numbers that you do not remember.

1) 9, 7, 1, 4, 2, 8
2) 3, 8, 4, 2, 1
3) 6, 1, 4, 9, 5, 8, 3, 2, 7
4) 5, 2, 9, 8, 7
5) 4, 9, 1, 7, 6, 3, 5
6) 3, 1, 4, 6
7) 8, 7, 4, 6, 1, 9, 2, 5, 3
8) 5, 2, 4, 7, 6, 1

Participant ID: _______

1) ____

2) ____

3) ____

4) ____

5) ____

6) ____

7) ____

8) ____

9) ____

10) ____

11) ____

12) ____

13) ____

14) ____

15) ____

16) ____

17) ____

18) ____

19) ____

Questions

1) To the best of your ability, please explain the stories that happened during the day in chronological order. In your explanation of the story, please refer to certain characters by describing their appearance. Also, please include descriptions of how sub-stories and characters are related to each other.

2) Can you rate your confidence in your understanding and explanation of the story? If 0% means that you have no understanding and are completely guessing, and 100% means that you are absolutely sure that you understand everything that is happening, can you give a percentage of your confidence?

3) For the next question, please list all of the events shown on the story cards, in any order. You can either use the title of the event or simply describe the event that was happening on each card. You will have 2 minutes and 30 seconds to list the cards, or you can tell use when you are done or cannot think of any more.

   Now we are going to ask some shorter questions.

4) What was the robber holding in the "Rob" scene?
5) What did the man with the blue shirt buy at the store?
6) What gifts were received in the "Gifts" scene?
7) What happened in the "Alarm" scene?
8) What color was the cake?
9) What did the sign say in the "Sale" scene?
10) What food products were present in the "Eat" scene?
11) What character or characters were in the "Gym" scene?
12) Describe the weather conditions during the "Yell" scene?

13) Explain what happened in the "Point" scene.
14) Explain what happened in the "Nap" scene and tell why you think that happened.
15) What happened in the "Wreck" scene, and can you give a possible explanation for what caused this to happen?
16) If you had to guess, what day of the week would you guess it was for this story, and why?

17) For this section, I am going to describe a character. For each character I describe:
    (I) Describe that character's day in as much detail as you are able.
    (II) How would you expect this character to be feeling at the end of the day, and why?
    (III) Describe an event or scene that you would expect that character doing after the events shown in the story cards.

    a. The man with a black hat
    b. The boy with a green, pointy hat
    c. The man with a blue shirt and black hair
    d. The man with green strips on his shirt
    e. The woman with a red shirt and long, brown hair
    f. The woman with a yellow shirt
    g. The boy with the red, baseball cap
    h. The man with the striped hat and an umbrella

18) When you were looking at the story cards, can you describe the process you were trying to use to figure out the story? Can you explain what you were thinking or any strategies you were using?

19) Can you explain how you came up with the answers to the all these questions about details of the story or individual story events? Did you think back to the images of the actual cards, or did you have story all in your head?
    Did you try to use the list on the display to help you?
    or
    Did you try to use the arrangement of cards on the display to help you?

    How? Do you think that it helped you?

20) For the blank labels/cards on the screen, do you remember any of the events? For the ones you remember, can you point to them and say what was there?

Scoring Rubric Part 1

ID	All Recall	Comp	Synth	Spatial	Event Recall Only	Comp and Synth	Confidence	Errors	Total Correct
	0	0	0	0	0	0	0	0	0

	Character (1 point Recall)	Events per character, within a logical and reasonable order (1 point Comprehension each) event needs to be placed in "logical and reasonable" order							Comp Score	Comp Error
0										
	Black hat	Eat, boy	Wave car boy	Rob store	Wreck, car	Police sketch			0	
	green hat boy	Open presents	Play ball	Break window	Lady yells				0	
	blue shirt / cook	Shop, cart	Buy food	Drive food	Cook cake	Give cake	Wreck, dirty hat	Dirty hat bed	0	
	green stripes man	Gym, weights	ATM, bank	Sports store	Get cake	Give presents			0	
	red shirt / brown hair / cry	Run, dog	Works, clerk store	Robbed	Police, sketch	cry			0	
	yellow shirt lady	Gym, treadmill	Mow grass	Nap	Break, window	Yell, boys			0	
	red, baseball cap boy	Alarm, wake up	Eat, black hat	Wave, car	Play, ball	Break window	Lady, yells		0	
	striped hat and umbrella	ATM, bank	Police, point	Rain, umbrella					0	
	police	Sketch, hat	Police point						0	

Scoring Rubric Part 2

Correct character identification requires enough detail to distinguish between characters and describe
the character either by events or appearance without ambiguity

An "error" is incorrectly describing an event or character in the story (without correction)

	Score (1 pt recall each)
Alarm	
Bank	
Bed	
Buy	
Cake	
Cart	
Cry	
Cook	
Eat	
Gifts	
Glass	
Gym	
Mow	
Nap	
Play	
Point	
Police	
Truck	
Rob	
Run	
Sale	
Wave	
Wet	
Wreck	
Yell	

Scoring Rubric Part 3

There was a man with a blue shirt and black hair, and a boy with a green, pointy hat. Can you explain any events that connected these characters throughout the day?

3 points **comprehension**:

Blue-shirt man cooks cake			Error
Blue-shirt man gives cake to man with striped shirt with presents			
Boy with green hat opens presents with man with striped shirt			

3 points **comprehension**:

boy with green hat plays baseball with boy with red hat	
Boy with red hat ate/waves to man with black hat	
man with black hat wrecks with man with blue shirt	

There was a man shopping at a sports store and a woman mowing the lawn. Can you explain any ways that these characters were connected throughout the events of the day?

1 points **comprehension**:

they were at the gym together			Error

4 points **comprehension**:

man with striped shirt buys ball and bat at sports store	
gives ball and bat as gifts to boy with green hat	
boys play baseball	
baseball breaks window of lady in yellow	

There was a woman running with a dog and a car wreck. How were the characters in these events connected?

3 points **comprehension**

woman works at store			Error
woman robbed by man with black hat			
man with black hat wrecks car			

2 points **comprehension**

man with blue shirt shops at store	
man with blue shirt in car wreck	

How was the boy with the red hat connected to the man with a striped shirt? — Error

2 points **comprehension**

striped shirt gives gifts to boy with green hat	
boy with green hat play baseball with red	

Can you come up with a sub-story of events that link the boy with red hat to the man with an umbrella in the rain? — Error

4 points **comprehension**

boy with red hat ate/waved to man with black hat	
black hat robs woman at store	
woman tells police about man with hat	
police point at man with striped hat	

Can you connect the man with the cart full of groceries to the man with the black hat?

1 point **comprehension**

car wreck			Error

1 point **comprehension**

Both at the same store with woman in red shirt	

Can you connect the man who was eating with the boy with a red baseball hat to the woman in the gym?

2 points **comprehension**

boy with red hat plays baseball			Error
ball breaks window			

Confidence Level:	

Scoring Rubric Part 4

1) What was the robber holding in the "Rob" scene?
   a. One point **detail recall** for money ☐
   a. One point **detail recall** for knife or sword ☐
2) What did the man with the blue shirt buy at the store?
   b. One point **detail recall** for bread ☐
   c. One point **detail recall** for "the box" (with orange and purple) ☐
3) What gifts were received in the "Gifts" scene?
   d. One point **detail recall** for baseball bat ☐
   e. One point **detail recall** for baseball ☐
4) What happened in the "Alarm" scene?
   f. One point **detail recall** for
   {(waking up) | (alarm clock) | (red cap kid sitting on bed)} ☐
5) What color was the cake?
   g. one point **detail recall** for pink or red ☐
6) What did the sign say in the "Sale" scene?
   h. one point **detail recall** for "Sports" or "Sport" ☐
7) What food products were present in the "Eat" scene?
   i. one point **detail recall** for apple ☐
   j. one point **detail recall** for banana ☐
   k. one point **detail recall** for milk or drink ☐
8) What character or characters were in the "Gym" scene?
   l. one point **detail recall** for woman in yellow ☐
   m. one point **detail recall** for man with green stripes ☐
9) Describe the weather conditions during the "Yell" scene?
   n. one point **detail recall** for cloudy ☐

Scoring Rubric Part 5

Comprehension/Detail recall

10) Explain what happened in the "Point" scene.

   o. One point **detail recall** for man with striped hat/umbrella

   p. One point **detail recall** for police

   q. One point **comprehension** for accusation or suspect based on because of hat — Error

      i. One extra point **comprehension** for specifying false/wrong accusation

11) Explain what happened in the "Nap" scene and tell why you think that happened.

   r. One point **detail recall** for mentioning lady in yellow — Error

   s. One point **comprehension** for the mentioning after gym or mowing grass

12) What happened in the "Wreck" scene, and can you give a possible explanation for what caused this to happen?

   t. One point **comprehension** for rain

   u. One point **comprehension** for hurrying from robbery — Error

   v. One point **comprehension** for waving to boy

13) If you had to guess, what day of the week would you guess it was for this story, and why?

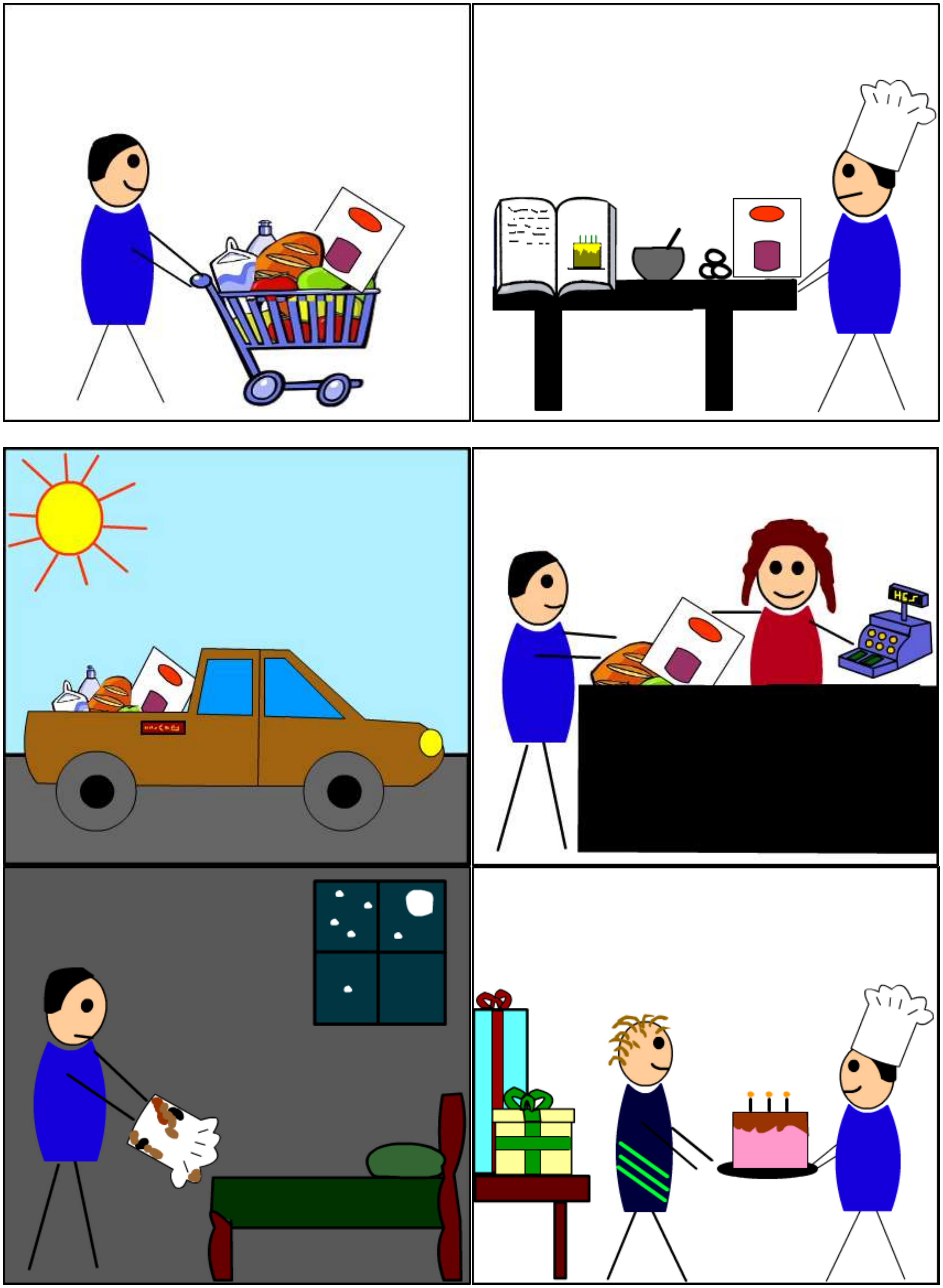
   w. One point **comprehension** for reasonable guess and explanation:

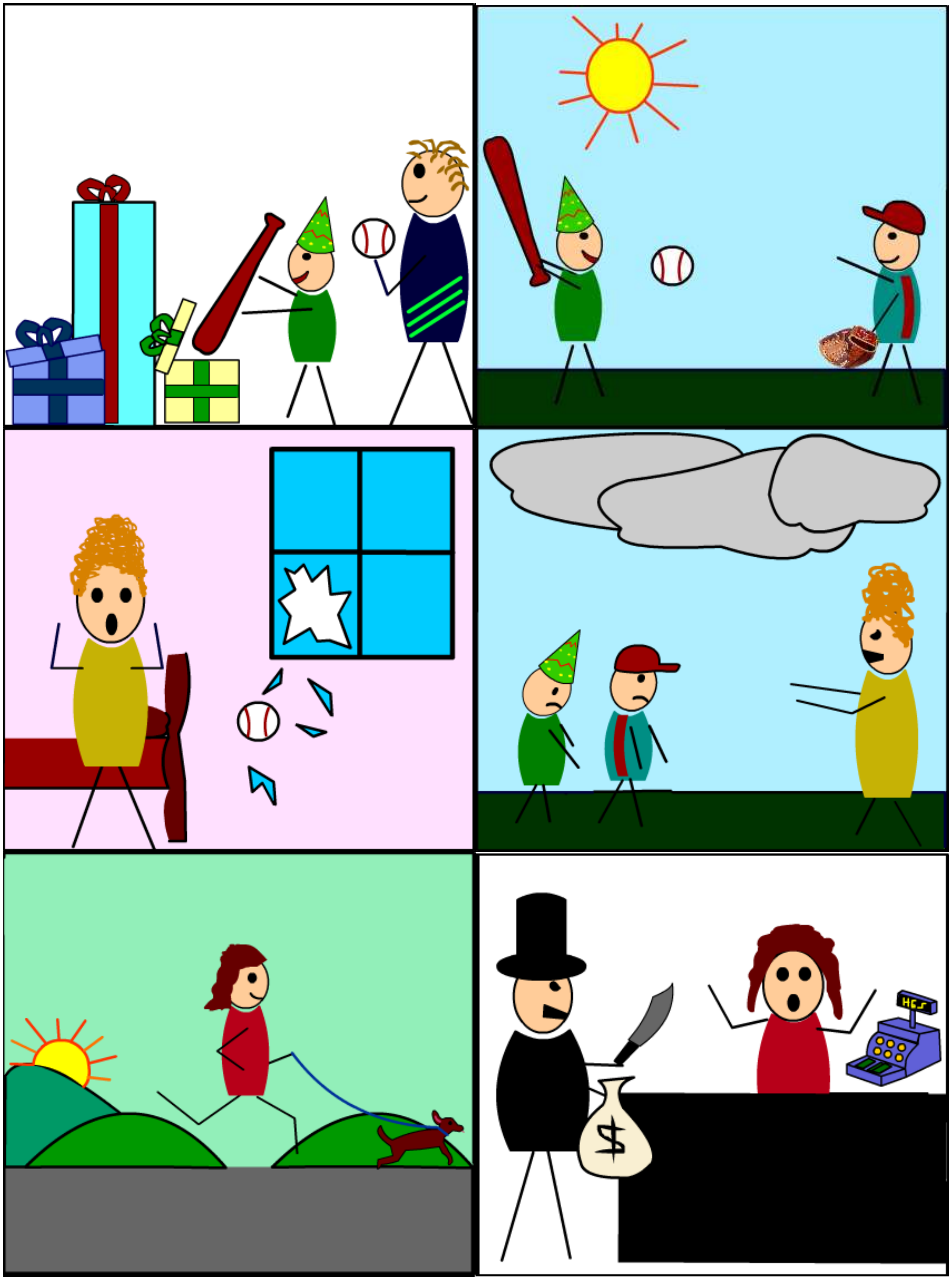
   (e.g., weekend, Saturday, or Sunday with explanation of people (adults) not being at work, doing chores/shopping, etc.)

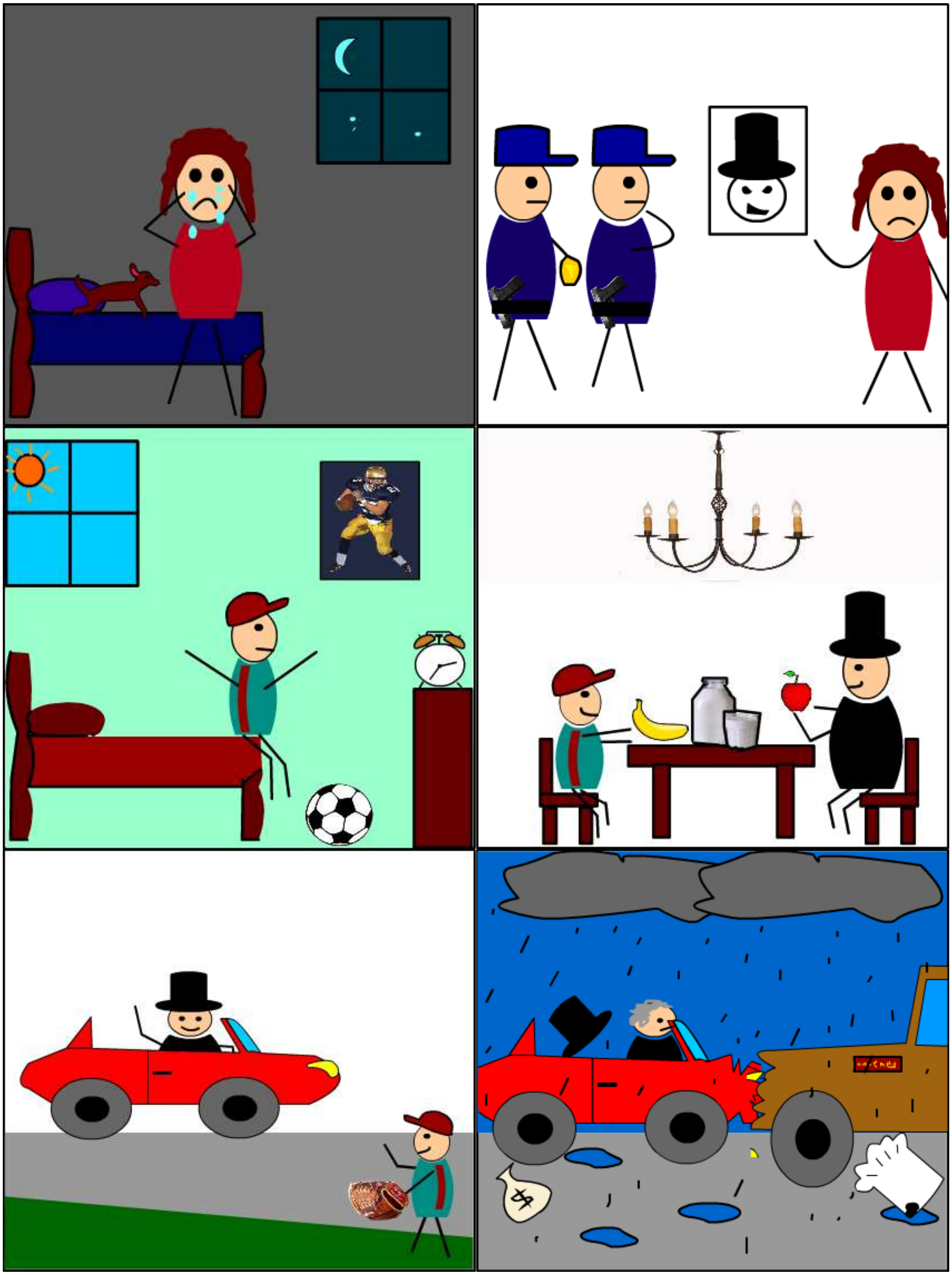
Character	**Emotion** (2 point synthesis)	**Next** (1 point synthesis)	Error
man with a black hat			
boy with a green, pointy hat			
man with a blue shirt and black hair			
man with green stripes on his shirt			
woman with long, brown hair			
woman with yellow shirt			
boy with red, baseball cap.			
man with the striped hat and an umbrella			

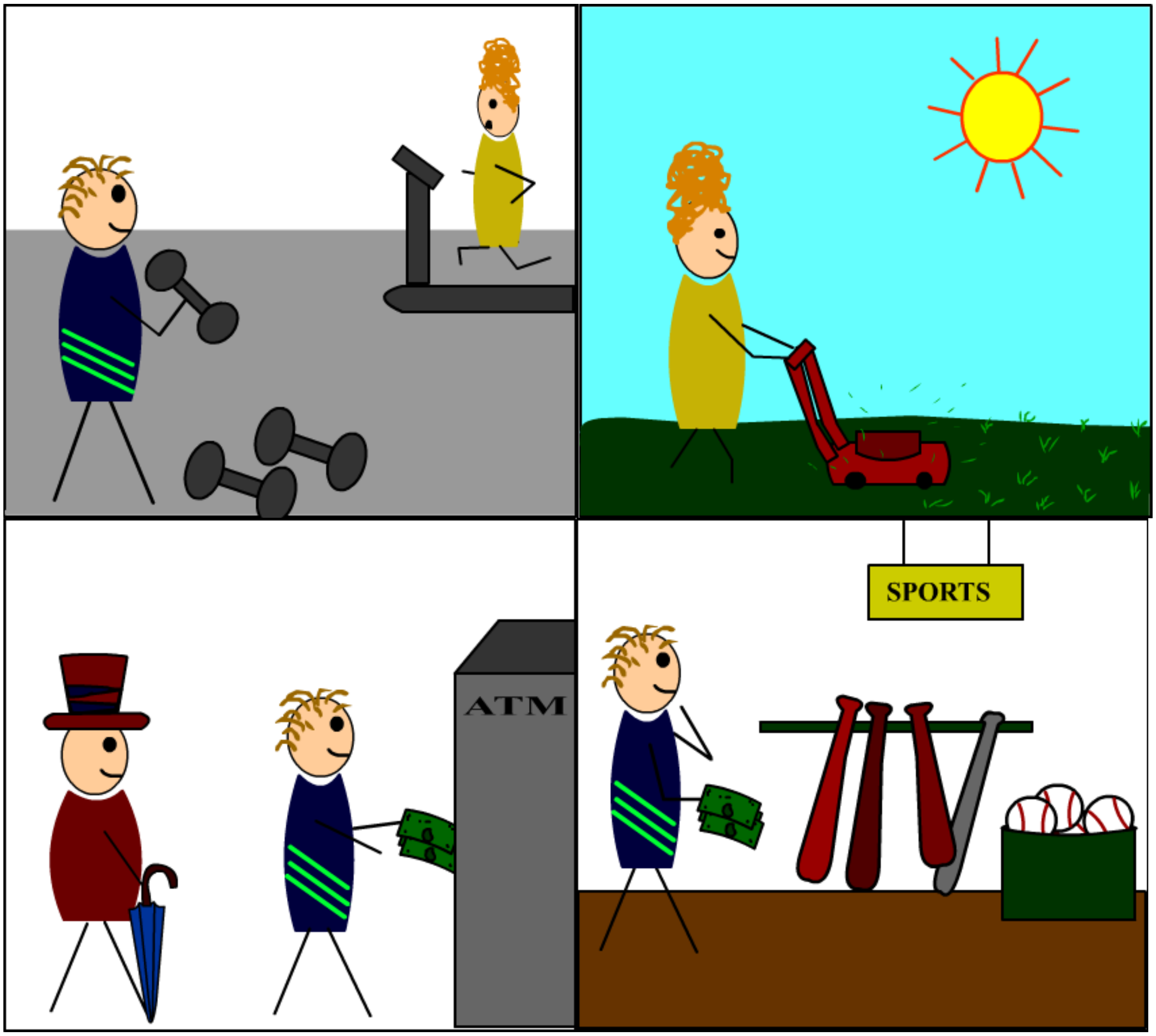
1) Spatial memory: one point for each correct location or area pointed towards

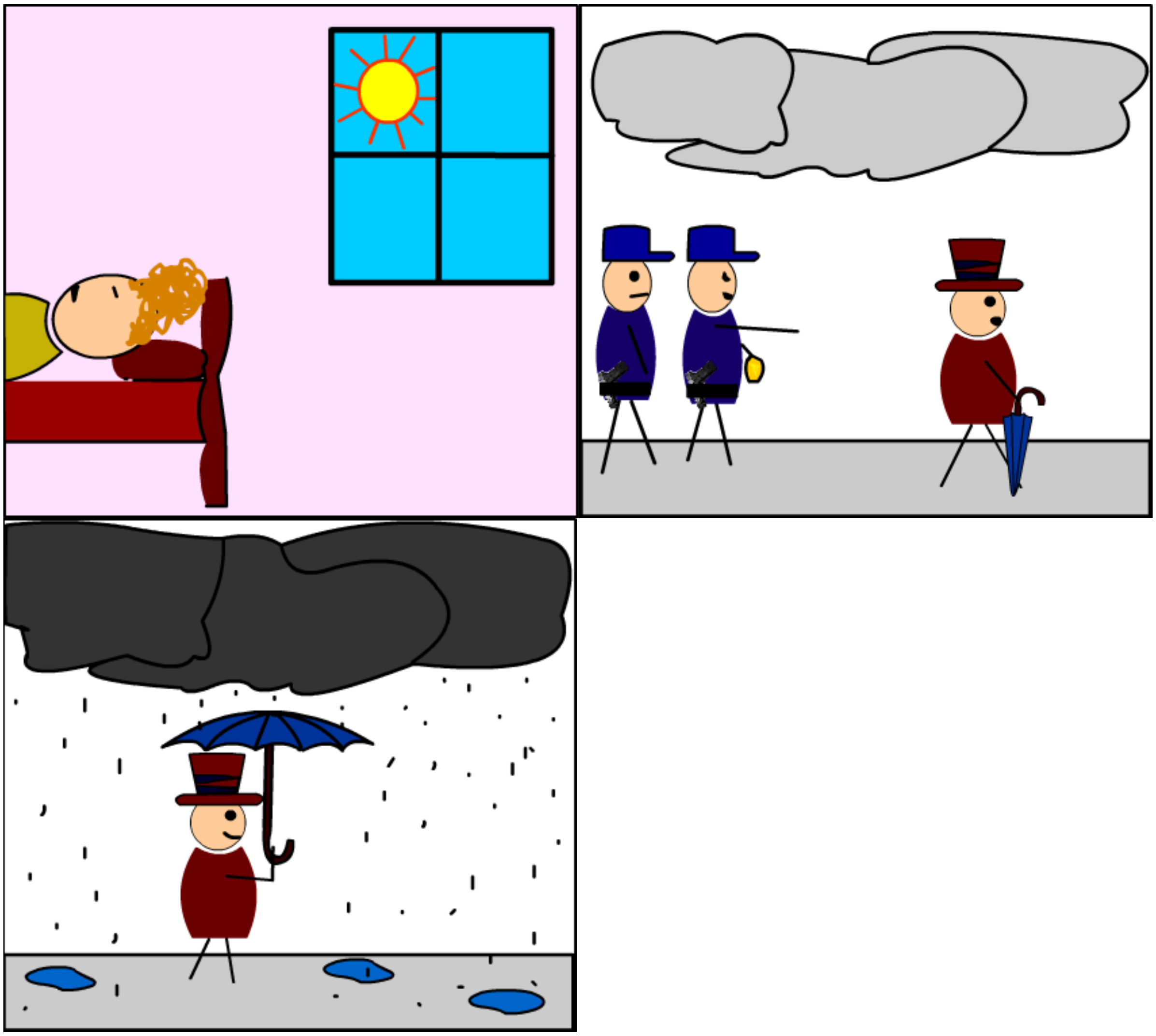
Data Set: Cartoon Story Panels








ATM
SPORTS



Appendix D: Experiment Documents for Experiment IV

VirginiaTech

Office of Research Compliance
Institutional Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24060
540/231-4606 Fax 540/231-0959
e-mail irb@vt.edu
Website: www.irb.vt.edu

MEMORANDUM

DATE: March 9, 2011

TO: Doug A. Bowman, Eric Ragan, Bireswar Laha, Karl Huber

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires October 26, 2013)

PROTOCOL TITLE: Effects of Navigation and Environmental Detail on Learning in 3D Virtual Environments

IRB NUMBER: 11-273

Effective March 9, 2011, the Virginia Tech IRB PAM, Andrea Nash, approved the new protocol for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at http://www.irb.vt.edu/pages/responsibilities.htm (please review before the commencement of your research).

PROTOCOL INFORMATION:
Approved as: **Exempt, under 45 CFR 46.101(b) category(ies) 2**
Protocol Approval Date: **3/9/2011**
Protocol Expiration Date: **NA**
Continuing Review Due Date*: **NA**
*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:
Per federally regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals / work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

cc: File

Informed Consent for Participant of Investigative Project

Virginia Polytechnic Institute and State University

Title of Project: Effects of Navigation and Environmental Detail on Learning in 3D Virtual Environments

Investigators: Dr. Doug Bowman, Eric Ragan, Bireswar Laha, Karl Huber

I. THE PURPOSE OF THIS RESEARCH/PROJECT

The purpose of this study is to achieve greater knowledge of what design features of 3D virtual environments affect learning. Such knowledge is important in order to understand how to design educational software applications that effectively support learning and allow for easy use.

II. PROCEDURES

You will be asked to complete a background questionnaire about yourself and your experience with computers and 3D games. Following, the experimenter will help familiarize you with the virtual environment display system. The experimenter will explain the learning task and provide instruction about how to view virtual content.

Your primary task for this study will involve learning about ten different animals. Animal fact sheets will be distributed within the virtual environment. After the learning phase, you will be asked to complete several tests (both computer-based and paper-based) to help evaluate your memory and understanding. We will conclude with an exit interview and debriefing about your learning process, opinions, or any other items you wish.

III. RISKS

There is minimal risk involved with this study, though some users experience discomfort from using large display systems. If you experience headaches, nausea, or other discomfort during the session, please feel free to step back from the display and inform the experimenter. You may terminate participation at any time.

IV. BENEFITS OF THIS PROJECT

Your participation in this project will provide information that may be used to inform the design of tools intended to aid learning. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed. Please leave a self-addressed envelope with the experimenter and a copy of the results will be sent to you.

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

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. Assessment data will be stored independently of any personally identifying information through the use of unique identification codes.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason. You are free not to answer any questions you choose not to.

VIII. APPROVAL OF RESEARCH

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

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

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

____ ________

Signature Date

____

Name (please print)

____

Age (please notify the experimenter if younger than 18 years)

Contact: phone or address or email address (OPTIONAL) ______________________________

____

____

____

Should I have any questions about this research or its conduct, I may contact:

Investigator: Eric Ragan Phone (814) 431-4576
Graduate Student, Computer Science Department (231-6931)
email: eragan@vt.edu

Principal Investigator: Dr. Doug A. Bowman Phone (540) 231-2058
Professor, Computer Science Department (231-6931)
email: bowman@vt.edu

Demographic Survey **Subject ID ________**

Background

Gender (circle one): Male Female

Age: ________

Degree level: graduate undergraduate

Major / Area of specialization: ______________________________

How many years are you into your program? __________________

If not student, other occupation: ____________________________

Vision

Do you regularly wear glasses or prescription contacts (circle one)? Yes No

Do you have any known color blindness (circle one)? Yes No

Computer Experience

Approximately how many hours a week do you use computers? ________________________

Approximately how many hours a week do you play video games? ______________________

What types of games?

Of this gaming, how many hours a week do you play **3D** video games?____________

Please describe any previous experience you have had with immersive virtual environments:

____

____

____

Number Span Test

I am now going to ask you take a quick auditory number span test. For this test, I will read out a sequence of numbers. After I finish reading the numbers, please write down the numbers in the exact order that they were read. Please do not write any of the numbers until I have finished reading the entire sequence.

For example, if I read out one-six-five-eight-nine, you would wait until I finish, and then write down one-six-five-eight-nine, as in the example on the answer sheet.

When writing down the sequence, please try to remember as many numbers as you can, and leave blank spaces for any numbers that you do not remember in the sequence.

1) 9, 7, 1, 4, 2, 8
2) 3, 8, 4, 2, 1
3) 6, 1, 4, 9, 5, 8, 3, 2, 7
4) 5, 2, 9, 8, 7
5) 4, 9, 1, 7, 6, 3, 5
6) 3, 1, 4, 6
7) 8, 7, 4, 6, 1, 9, 2, 5, 3
8) 5, 2, 4, 7, 6, 1
9) 2, 9, 3, 6, 4, 8, 7, 1, 3, 5, 9
10) 6, 4, 9, 3, 1, 4, 7
11) 1, 7, 4, 3, 8, 5, 2 , 6
12) 4, 6, 1, 3, 9, 1
13) 2, 7, 5, 8, 1, 3, 9, 8, 7, 3, 4, 6
14) 7, 2, 5, 8, 2, 9, 4, 1, 3
15) 8, 1, 3, 5, 7, 6
16) 9, 5, 3, 4, 6, 2, 8, 1
17) 5, 9, 1, 7, 5, 6, 2, 1, 5, 3, 9
18) 2, 4, 3, 6, 4, 5, 1, 3, 5, 7
19) 3, 1, 9, 4
20) 8, 7, 4, 1, 4, 6, 2
21) 5, 2, 8, 6, 1, 5
22) 9, 3, 8, 4, 1, 6, 1, 7
23) 6, 8, 2, 9, 8, 3, 5, 3, 9, 2, 4, 7

Example: 1 6 5 8 9 ___ ___ Participant ID: _______

1) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

2) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

3) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

4) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

5) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

6) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

7) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

8) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

9) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

10) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

11) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

12) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

13) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

14) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

15) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

16) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

17) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

18) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

19) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

20) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

21) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

22) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

23) ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

Post-Session Interview

1) Can you describe the process you used to try to learn the information? What types of strategies did you use?

    a. What were you trying to do to learn the information?

    b. What were you focusing on? Did you pay more or less attention to any specific category or information type, like weight, location, habitat, etc. Why?

    c. Did you find yourself focusing more or less on any specific animal cards? Were any harder or easier? Why?

    d. Were you trying to rehearse the information? If so: How? Do you think it helped?

    e. Did you always just focus on the card directly in front of you, or did you try to refer back to other cards? If so: Can you explain how? Do you think it helped?

    f. For landmark conditions: Did you notice or pay attention to the landmark objects or different ground textures? If so: Did that affect your learning process in any way? (Example: Did you try to use them at all to help you? Or do you think they were distracting?)

2) What did you try to do to remember the information during the tests? What were you thinking back to? (Example: Did you have just a list of verbal facts in your head? Were you trying to visualize the actual fact cards? Any other types of methods that you can explain?)
    a. Did you use the environment or the layout at all to help you organize or remember the information?
    b. Did you ever visualize the environment to try to help remember the information?
    c. Did you ever try to refer back to the locations where the cards were?

3) What did you think about the movement through the environment?
    a. Did you have any problems with the motion in the environment? Was it easy? Did it seem ok? Was it distracting? Did it complicate things?

    b. Did you have any problems maintaining orientation in the environment? Did it matter?

    c. Automatic: What did you think about the amount of time you had at each card? Was it too much, too fast, just right? What about the order that you viewed the cards? Would you have viewed things differently if you could have controlled movement on your own?

    d. Manual: What did you think about the motion control? Was it easy? Was it fast enough, or too fast? Did you have to think about how to go move where you wanted to go? Was this distracting? Do you think this affected the learning process?

Is there anything else you want to tell me about this overall? Was it fun? Was it really terrible? Was it stressful? Why?

Data Set: Fabricated Animal Facts

Forden

Location	Australia
Habitat	Desert
Avg Weight	10 kg
Avg Body Length	75 cm
Conservation Status	Vulnerable

Serital

Location	Africa
Habitat	Mountains
Avg Weight	15 kg
Avg Body Length	90 cm
Conservation Status	Least concern

Lamgerden

Location	Europe
Habitat	Mountains
Avg Weight	6 kg
Avg Body Length	110 cm
Conservation Status	Endangered

Hetsaa

Location	Australia
Habitat	Caves
Avg Weight	0.025 kg
Avg Body Length	7 cm
Conservation Status	Least concern

Kantu

Location	Europe
Habitat	Forest
Avg Weight	1 kg
Avg Body Length	55 cm
Conservation Status	Endangered

Mulnet

Location	North America
Habitat	Mud
Avg Weight	0.008 kg
Avg Body Length	10 cm
Conservation Status	Least concern

Tinran

Location	South America
Habitat	Sea water
Avg Weight	0.003 kg
Avg Body Length	4 cm
Conservation Status	Endangered

Saugawar

Location	North America
Habitat	Swamp
Avg Weight	3 kg
Avg Body Length	90 cm
Conservation Status	Vulnerable

Arapaim

Location	Asia
Habitat	Freshwater
Avg Weight	100 kg
Avg Body Length	200 cm
Conservation Status	Endangered

Wolmati

Location	Europe
Habitat	Grasslands
Avg Weight	0.02 kg
Avg Body Length	25 cm
Conservation Status	Vulnerable

Appendix E: Experiment Documents for Experiment V

VirginiaTech

Office of Research Compliance
Institutional Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24060
540/231-4606 Fax 540/231-0959
e-mail irb@vt.edu
Website: www.irb.vt.edu

MEMORANDUM

DATE: May 19, 2011

TO: Doug A. Bowman, Eric Ragan

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires October 26, 2013)

PROTOCOL TITLE: Immersive Virtual Data Fusion Environments

IRB NUMBER: 11-484

Effective May 19, 2011, the Virginia Tech IRB Chair, Dr. David M. Moore, approved the new protocol for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at http://www.irb.vt.edu/pages/responsibilities.htm (please review before the commencement of your research).

PROTOCOL INFORMATION:
Approved as: **Expedited, under 45 CFR 46.110 category(ies) 7**
Protocol Approval Date: **5/19/2011**
Protocol Expiration Date: **5/18/2012**
Continuing Review Due Date*: **5/4/2012**
*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:
Per federally regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals / work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Informed Consent for Participant of Investigative Project
Virginia Polytechnic Institute and State University

Title of Project: Immersive Virtual Data Fusion Environments

Investigators: Dr. Doug Bowman, Eric Ragan

I. THE PURPOSE OF THIS RESEARCH/PROJECT

The purpose of this study is to achieve greater knowledge of what design features of 3D virtual environments affect performance for data visualization tasks. We are investigating methods and display properties in order to further knowledge of how to visualize and explore a variety of data types within an integrated visualization. By providing a visualization environment capable of integrating spatial and physical data with other types of scientific data, information could be explored within the context of the location from which it was collected. By studying how software users complete various data analysis tasks in a VE, we hope to gain greater knowledge of how display properties and viewing techniques affect data exploration.

II. PROCEDURES

You will be asked to complete a background questionnaire about yourself and your experience with computers and 3D games. You will also be asked to complete a short cube-comparison test. Following, the experimenter will explain the data analysis task and help familiarize you with the virtual environment display system. You the experimenter will guide you through a practice data analysis task. After this practice session, you will be asked to answer several questions about a new data set in a new visualization environment.

Your primary task for this study will involve identifying data values and describing relationships between different data types. Different colors will indicate different data types and numeric labels will be provided within the environment. After this data analysis session, you will be asked to complete a short computer-based test to help evaluate your overall memory and understanding of the data layout. We will conclude with an exit interview and debriefing about your learning process, opinions, or any other items you wish.

III. RISKS

There is minimal risk involved with this study, though some users experience discomfort from using large display systems. If you experience headaches, nausea, or other discomfort during the session, please feel free to step back from the display and inform the experimenter. You may terminate participation at any time.

IV. BENEFITS OF THIS PROJECT

Your participation in this project will provide information that may be used to inform the design of tools intended to aid data analysis and information processing. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed. Please leave a self-addressed envelope with the experimenter and a copy of the results will be sent to you.

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

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. Assessment data will be stored independently of any personally identifying information through the use of unique identification codes.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason. You are free not to answer any questions you choose not to.

VIII. APPROVAL OF RESEARCH

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

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

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

____ ________
Signature Date

____
Name (please print)

____
Age (please notify the experimenter if younger than 18 years)

Should I have any questions about this research or its conduct, I may contact:

Investigator: Eric Ragan Phone (814) 431-4576
Graduate Student, Computer Science Department (231-6931)
email: eragan@vt.edu

Principal Investigator: Dr. Doug A. Bowman Phone (540) 231-2058
Professor, Computer Science Department (231-6931)
email: bowman@vt.edu

Demographic Survey   Subject ID ________

Background

Gender (circle one):   Male   Female

Age: ________

Degree level: graduate   undergraduate

Major / Area of specialization: ________________________________

How many years are you into your program? ___________________

If not student, other occupation: ______________________________

Vision

Do you regularly wear glasses or prescription contacts (circle one)?   Yes   No

Do you have any known color blindness (circle one)?   Yes   No

Computer Experience

Approximately how many hours a week do you use computers? ________________________

Approximately how many hours a week do you play video games? ______________________

What types of games?

Of this gaming, how many hours a week do you play **3D** video games?_____________

Please describe any previous experience you have had with immersive virtual environments:

____

____

____

Introduction to the environment
1) Instruct on navigation and practice
2) Provide top-down map of the environment
3) Turn area labels on
4) Confirm understanding of the relationship between top-down map and VE layout
5) Explain data types and buttons, left to right

Practice

Search Task Instruction
For each of these questions, you will have a maximum of 5 minutes to determine the minimum or maximum value. You will have to find the highest or lowest value and tell me the area name where you found it. Afterwards, you will have to that value and point to it. For these search questions, you should try to answer as quickly as possible. It is better to make a guess even if you are not 100% sure of the correct answer. Please make a guess when you are about 70% confident that you have the right answer. Until the time limit is reached, you can still give a different answer later. Make sure that you know where the value is for your answer so that you can point to it at the end of each question.

Search Strategy Instruction
You can use whatever strategy you want to look through the data values and try to answer the questions. I recommend using the colors to visually scan for areas with high concentrations of extreme values. You can then scan the numbers in that area to find the highest or lowest value in that area. You should try to remember your best guess and where it was before moving on to scan a different area.

<u>Search and compare</u>

1) Which area has the lowest values for iron content, and what is the lowest value?
- Area Y
- 13.2

2) Which area has the highest values for nitrogen content, and what is the nitrogen value?
- Area Z
- 33.1%

Practice: Relationships

Relationship Task Instruction
For questions in the next section, your job will be to determine the relationship between two types of information. For each question, I will specify two information types. Your job is to figure out if and how the data values change with respect to each other. The possible relationships are: direct relationship, inverse relationship, or no relationship. If the information types are directly related, values for both data types generally increase or decrease together. If the information types are inversely related, when the value for one data type increase, the other decreases. One type gets higher in areas where the other type gets lower. The other option is that there is no relationship. If there is no relationship between data types, values of the two data types change independently of each other, so higher or lower values for one type does not mean that the other data types will have higher or lower values.

To determine the relationship, you will need to look at multiple areas of the cave. It will not be enough to figure out whether or not there is a relationship between the data types just by considering one area--you need to look for overall patterns. Also note that there can still be relationships even if absolutely every data point does not follow the pattern. You need to make your best judgment about what is happening overall.

For each relationship question, you will have a 4 minute time limit. You will only get one guess for the relationship, so you should try to be confident in your answer before giving your answer. But you should still try to answer as quickly as you can without sacrificing accuracy.

Relationship Strategy Instruction
For relationship tasks, if is often useful to look in areas with extreme values for one of the data types, and then looking at the values of the other data type in that area. You will have to do this in multiple areas to understand the overall relationship in the entire cave.

<u>Relationship Questions</u>

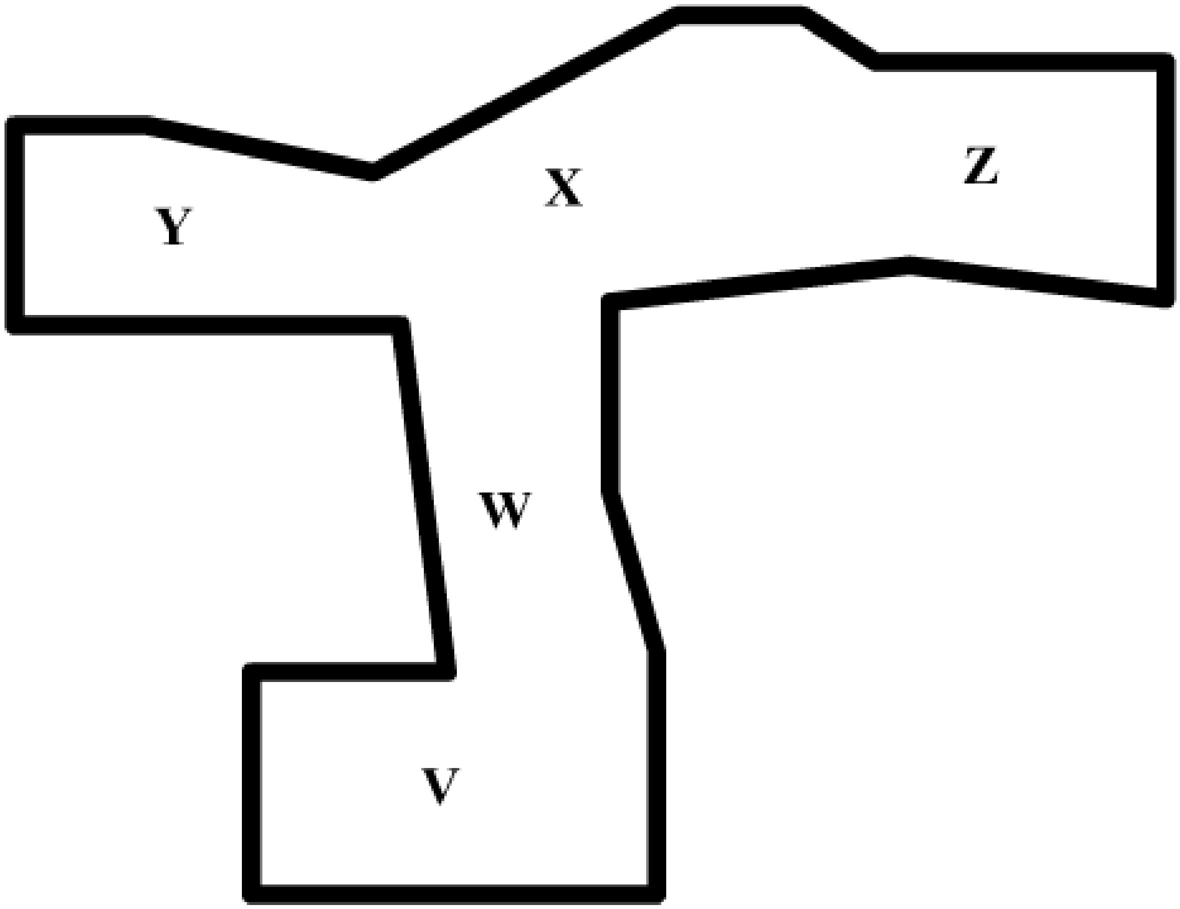
1) What is the relationship between surface elevation and surface temperature (small blue-purple-red data spheres)?

-lower is warmer, higher is colder

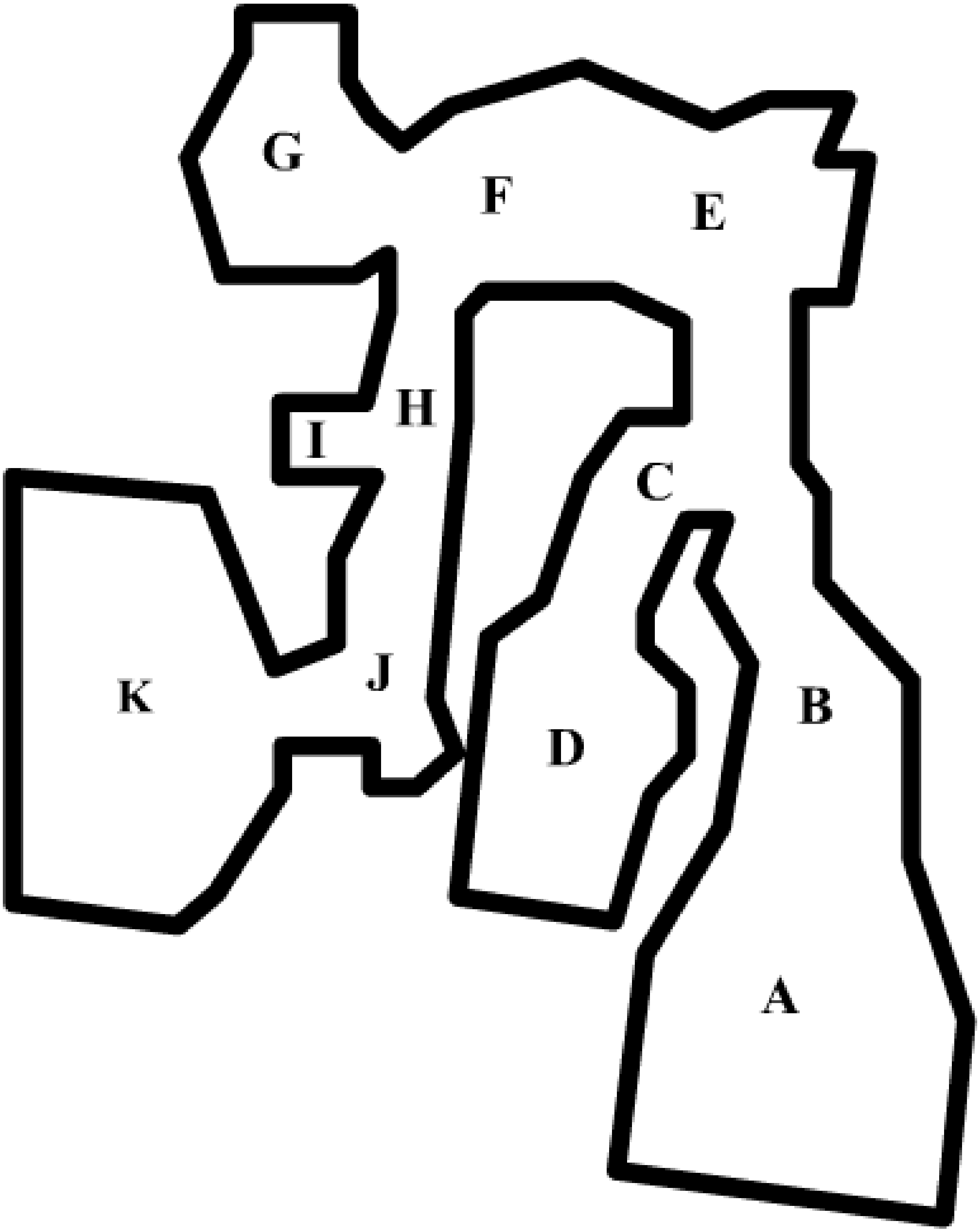
2) What is the relationship between sub-surface depth (yellow-green bars) and zinc content (large orange clouds)?

-no relationship

Practice Environment Map



Main Environment Map



Real Questions: <u>Search</u>

1) Which area has the highest value for iron content, and what is the highest value?

- A
- 21.4

Value	Area	Time	Confidence

Notes

2) Which area has the lowest value for temperature, and what is the temperature value?

- D
- 27.1

Value	Area	Time	Confidence

Notes

3) Which area has the highest subsurface depth, and what is that value?

- A
- 1.29

Value	Area	Time	Confidence

Notes

4) Which area has the highest values for oxygen content, and what is the oxygen value?

- K
- 9.1

Value	Area	Time	Confidence

Notes

5) Which area has the highest value for temperature, and what is the temperature value?

- K
- 58.9

Value	Area	Time	Confidence

Notes

6) Which area has the highest values for nitrogen content, and what is the nitrogen value?

- I
- 15.0

Value	Area	Time	Confidence

Notes

Real Questions: Relationships

1) What is the relationship between iron content (small yellow-orange-red squares) and zinc content (large orange spheres)?

- inverse

2) What is the relationship between sub-surface depth (yellow-green bars) and surface temperature (small blue-purple-red data spheres)?

- none

3) What is the relationship between surface elevation and zinc content (large orange clouds)?

- none

4) What is the relationship between the oxygen content (large blue clouds) and surface temperature (small blue-purple-red data spheres)?

- direct

5) What is the relationship between sub-surface depth (yellow-green bars) and iron content (small yellow-orange-red squares) ?

- direct

6) What is the relationship between iron content (small yellow-orange-red squares) and surface temperature (small blue-purple-red data spheres)?

- none

7) What is the relationship between sloped floor surfaces and sub-surface depth (yellow-green bars)?

- lower sub-surface depths

Post-Session Interview

Did you think that any tasks easier or harder than others? Why?

Can you explain how you used different colors to help you answer the questions?

Did you find it hard to navigate the virtual cave? Did you often feel lost or disoriented in the environment?

Was it hard to remember which buttons did what? Was it ever distracting? Did you have to think about it, or did it feel mostly automatic?

What did you think about the movement through the environment? Was it easy? Was it ever distracting? Was it too fast or too slow?

Did your strategy or comfort with performing the tasks change throughout the study? Did anything become more confusing or easier?

Do you have any other comments about this study or the task? Is there anything else that you want to tell me? Do you have any other questions for me?

Appendix F: Experiment Documents for Case Study with Causes of World War I Virtual Environment

VirginiaTech

Office of Research Compliance
Institutational Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, VA 24060
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE:	November 19, 2012
TO:	Doug A Bowman, David Hicks, Eric Dennis Ragan
FROM:	Virginia Tech Institutional Review Board (FWA00000572, expires May 31, 2014)
PROTOCOL TITLE:	Learning History in a 3D Environment
IRB NUMBER:	**12-995**

Effective November 19, 2012, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 6,7**
Protocol Approval Date:	**November 19, 2012**
Protocol Expiration Date:	**November 18, 2013**
Continuing Review Due Date*:	**November 4, 2013**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

Informed Consent for Participant of Investigative Project
Virginia Polytechnic Institute and State University

Title of Project: Learning History in a 3D Environment

Investigators: Dr. Doug Bowman, Eric Ragan, Dr. David Hicks

I. THE PURPOSE OF THIS RESEARCH/PROJECT

The purpose of this study is to achieve greater knowledge of how to design 3D virtual environments to support learning and investigation.

II. PROCEDURES

You will be asked to complete a background questionnaire about yourself and your experience with computers and 3D games. We will then ask you to take a short cube rotation test. Next, we will ask you to complete a short multiple choice test about the First World War. Following, the experimenter will help familiarize you with the virtual environment display system. The experimenter will explain the search task and provide instruction about how to view virtual content.

Your primary task for this study will involve learning about the causes of WWI in a virtual environment. You will view different information in a 3D world and use it to develop your understanding about the causes of the war. After the learning phase, we will ask you to take another short multiple-choice test and to write an essay explaining the causes of the war. We will conclude with an exit interview and debriefing about the experiment. We will ask about the techniques you used while using the software, your opinions about the task, your thoughts on your comfort and performance with the system, or about any other items you wish.

III. RISKS

There is minimal risk involved with this study, though some users experience discomfort from looking at 3D visualizations. If you experience headaches, nausea, or other discomfort during the session, please tell the experimenter before taking a break. You may terminate participation at any time.

IV. BENEFITS OF THIS PROJECT

Your participation in this project will provide information that may be used to inform the design of virtual training tools. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed. Please leave a self-addressed envelope with the experimenter and a copy of the results will be sent to you.

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

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. Assessment data will be stored independently of any personally identifying information through the use of unique identification codes. Audio and video recording may be used to help record your responses. This material will only be used to help the research team to review your responses and observe your use of the software. This material will be kept confidential and will not be shared with others outside of the approved research team.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason. You are free not to answer any questions you choose not to.

VIII. APPROVAL OF RESEARCH

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

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

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

____ ________
Signature Date

____
Name (please print)

____
Age (please notify the experimenter if younger than 18 years)

Contact: phone or address or email address (OPTIONAL) ______________________________
____
____
____

Should I have any questions about this research or its conduct, I may contact:

Investigator: Eric Ragan Phone (814) 431-4576
Graduate Student, Computer Science Department (231-6931)
email: eragan@vt.edu

Principal Investigator: Dr. Doug A. Bowman Phone (540) 231-2058
Professor, Computer Science Department (231-6931)
email: bowman@vt.edu

IRB Chair: Dr. David Moore, Phone (540) 231-4991
2000 Kraft Drive Suite 2000,
Blacksburg VA 24060
email: moored@vt.edu

Participant #: [ ]

Background Questionnaire

Please help us to categorize our user population by completing the following items.

Date: [ ]

Gender (select one):

○ Male ○ Female

Age:

[ ]

Do you wear glasses or contact lenses (select one)?

○ No ○ Yes

If so, which do you wear normally?

○ Glasses ○ Contacts

Are you wearing them right now?

○ Yes ○ No, but I have my vision still corrected ◉ No, other: [ ]

Occupation (if student, indicate graduate or undergraduate):

[ ]

Major/Area of Specialization (if student):

[ ]

Rate your tiredness level today (select one):

○ very tired ○ somewhat tired ○ a little tired ○ not tired at all

Do you have any experience with playing the Wii, Playstation Move or

any other video game that uses motion tracking?

○ Yes ○ No

If yes, how many hours per week, on average, do you play? [ ]

Do you have any experience with playing video games other than the ones described above?

○ Yes ○ No

If yes, how many hours per week, on average, do you play? [ ]

Do you have any experience with playing video games with stereo (in 3D)?

○ Yes ○ No

If yes, how many hours per week, on average, do you play? [ ]

What type of video games do you usually play (select all that apply)?

- [ ] First-person shooting games (e.g. Half Life, Battlefield, etc...)
- [ ] Sports games (e.g. Need for speed, Madden, etc..)
- [ ] Massive multiplayer online games (e.g. World of Warcraft)
- [ ] Real-time strategy games (e.g. Starcraft)
- [ ] Mobile devices casual games (e.g. iPhone, iPad, etc...)
- [ ] Motion capture casual games (e.g. Wii Sports, Wii Fit, etc...)
- [ ] Social games (e.g. Facebook)
- [ ] Third-person action games (e.g. Grand Theft Auto, Gears of War, etc...)

Other: [ ]

Do you have any experience with virtual environments / virtual reality?

○ Yes ○ No

If yes, please explain:

Do you have experience using multiple computer monitors or very large screens? Please explain.

This experiment involves learning about history and the causes of WWI. Please make a guess about your knowledge about WWI, rating your level of knowledge on a scale from one to seven.

- (1) I have no idea when it was or who was involved
- (2)
- (3)
- (4)
- (5)
- (6)
- (7) I am very confident about my knowledge of WWI

Please briefly explain why you rated your knowledge of WWI as you did above.

Multiple Choice Test Questions

1) Which countries were allied with Britain at the start of the First World War?
   France and Austria-Hungary
   Russia and Spain
   Spain and Italy
   Russia and France
   Italy and Russia
   Austria-Hungary and Italy

2) Which countries were allied with Germany at the start of the First World War?
   France and Austria-Hungary
   Russia and Spain
   Spain and Italy
   Russia and France
   Italy and Russia
   Austria-Hungary and Italy

3) In what year did the First World War start?
   1904
   1912
   1914
   1922
   1939
   1945

4) Archduke Franz Ferdinand was from which country?
   Serbia
   Austria
   Russia
   Italy
   France
   Britain

5) Which two countries were most involved in developing war ships in the decade before the war?
   France and Germany
   Britain and Austria
   Britain and Germany
   Italy and Russia
   Russia and Austria-Hungary
   France and Serbia

6) Which two countries had direct conflicts in Morocco before the war?
France and Germany
Britain and Italy
Britain and Germany
Austria-Hungary and Russia
Russia and Italy
France and Austria-Hungary

7) Which country supported Serbia most strongly in the years leading up to the war?
Austria-Hungry
Britain
France
Germany
Italy
Russia

8) What country or territory did Austria take over a few years before the war started?
Alsace Lorraine
Serbia
Morocco
Poland
Bosnia and Herzegovina
Bulgaria

Question/Prompt

Explain the causes of the First World War, and include both short-term and long-term causes. Your account should also explain who you think was responsible for war. Justify your response using specific events and facts from the virtual environment.

Note Sheet

Participant ID: ____________

Jumps Learning: ___________

Done Time Learning: ________

Jumps Testing: ____________

Done Time Essay: ___________

Notes (learning and testing)

A topic	
A header	
A image	
A1	
A2	
A3	
A4	

A5	
A6	
B topic	
B header	
B image	
B1	
B2	
B3	
C topic	
C header	
C image	
C1	
C2	
D topic	
D header	
D image	
D1	
D2	
D3	
D4	
E topic	
E header	
E image	
E1	
E2	
F topic	
F header	
F image	
F1	
F2	
F3	
F4	
F5	
G topic	
G header	
G image	
G1	
G2	
H topic	
H header	
H image	
H1	
H2	
J	
K	
L	
M	
N	
O	
P	
???	

Participant #: [ ]

Simulator Sickness Questionnaire

Select below any of the symptoms that you experienced throughout the study

General Discomfort

○ None ○ Slight ○ Moderate ○ Severe

Fatigue

○ None ○ Slight ○ Moderate ○ Severe

Headache

○ None ○ Slight ○ Moderate ○ Severe

Eyestrain

○ None ○ Slight ○ Moderate ○ Severe

Difficult focusing

○ None ○ Slight ○ Moderate ○ Severe

Increased salivation

○ None ○ Slight ○ Moderate ○ Severe

Sweating

○ None ○ Slight ○ Moderate ○ Severe

Nausea

○ None ○ Slight ○ Moderate ○ Severe

Difficulty Concentrating

○ None ○ Slight ○ Moderate ○ Severe

Fullness of head

○ None ○ Slight ○ Moderate ○ Severe

Blurred vision

○ None ○ Slight ○ Moderate ○ Severe

Dizzy (eyes open)

○ None ○ Slight ○ Moderate ○ Severe

Dizzy (eyes closed)

○ None ○ Slight ○ Moderate ○ Severe

Vertigo

○ None ○ Slight ○ Moderate ○ Severe

Stomach awareness

○ None ○ Slight ○ Moderate ○ Severe

Burping

○ None ○ Slight ○ Moderate ○ Severe

Post-Session Interview

Tell me about your strategy or approach you took when going the virtual environment.
How did you decide what to look at and for how long? Did you go around in any particular order? Did you jump around randomly? Did you ever jump up to the viewpoints in the sky? When? How often? Why?

What did you think of the task? Was it hard or easy? How hard/easy? Was it boring? Were you able to pay attention and try the whole time, or do you think you lost attention? Did you feel like you had enough time? Did you feel rushed or under pressure for time?

Did you have any kind of problems with the application and task that you can tell me about? What made the task difficult? Was anything distracting?

How was the travel? Was it difficult or easy? Did you have to focus on how to get to where you wanted to go, or was it pretty mindless? Was it distracting to have to jump to different places or to rotate your view?

(If CAVE) Did you use multiple walls and the floor, or did you mostly just use one (if so, which one?)

Do you have any comments on how the information was organized in the application? Would you have organized things any differently?

After you had looked through the environment for a little while, was it easy to find things? Did you feel like you were wasting time searching for things that you saw before? Was there anything that made this better or worse? What helped you to find things?

What did you think about the number of groups and the number of things in each group? Were there too many places to go too? Did you wish things were more spread out?

Did you ever just look around the environment, or were you always pretty much just focused on the information directly in front of you? Did you ever look back to other places where you had already been? Why? How often? Do you think this helped you to remember different pieces of information or organize your thoughts?

What did you think about the pictures in the environment? Did you pay any attention to them? Were they helpful or distracting? Both? Neither? Did you use them to help you get around? Did you ever just look around and refer to pictures to help remember things?

When you were done in the virtual environment and writing your essay and taking the test again, can you tell me anything about your strategy for thinking about your answers?

Did you ever think back to the environment, or did you mostly just have all the information organized in your head?
Did you imagine or look through it? Did you try to think about how the information was organized or where things were?

Did you try to try to visualize the information cards? Why? Can you try to tell me when you did or didn't? If you did, do you think it helped?

Did you ever try to imagine the images from the environment?

Do you remember where things were? Do you remember what type of information was in these groups? For each of these groups, do you remember what was on the cards in each group?

Do you have any other comments or questions at all? Things that you think I should know that I didn't specifically ask about? Things that you kind of liked? Things that you hated?

Preliminary Scoring Rubric Part 1

Participan	HighLevel	DetailScore	Flow	Responsbility	TotalScore
	0	0	0	0	0
		High-level category	(Need only mention these without explanation)		
		Militarism			
		Nationalism			
		Imperialism/Colonies/Land			
		Alliances/chain reaction			
		Event/Tension name	**Details**		
		Bosnia and Herzegovina			
			Austria took over Bosnia and Herzegovina		
			Russia and Serbia protested		
			Germany supported Austria		
			Russia and Serbia backed down because of Germany		
			Austria felt confident that Germany would back it in future		
		Morocco			
			France was trying to take control in Morocco, colonies		
			German Kaiser visited Morocco and announced German support for Morocco's independence		
			1905		
			French mad		
			Britain and France united in opposition		
			Germany sent a gunboat to Morocco		
			1911		
			Britain and France again united in opposition		
		Arms race			
			Germany more than doubled army in a few years		
			France, Germany, Italy, Austria increased army 1910-1914		
		Naval rivalry			
			Britain		
			Germany		
			Dreadnoughts		
			1898 – 1914		
		Assassination			
			Austria felt threatened by Serbia's success and army in war in the Balkans		
			Franz Ferdinand from Austria		
			Austria blamed Serbia		
			demands/ultimatum		
			Austria declares war on Serbia		
		Alliances			
			Britain, France, Russia		
			Germany, Italy, Austria		

Preliminary Scoring Rubric Part 2

Countries	France
France	[redacted]
Britain	cooperated, agreed about Morocco
Germany	Germany formed after defeating France in war. Germany took territory (Alsace Lorraine) from France. France wanted it back; Germany feared retaliation.
Italy	[redacted]
Russia	friendship formed when France helped Russia with loans to develop industries
Austria	[redacted]
Serbia	[redacted]

Germany
[redacted]
wanted to be seen as a world power. wanted more overseas colonies
Italy joined the alliance with Germany and Austria to increase power
Germany worried about being surrounded by France and Russia. Germany worried about Russia's army build up
Austria allied with Germany to protect itself from Russia and Serbia. Germany allied with Austria-Hungary to protect itself from French retaliation from their war
[redacted]

Italy
[redacted]
settled and looking to show off its power. Interested in colonies
[redacted]
Italy joined the alliance with Germany and Austria to increase power
[redacted]

Russia
[redacted]
Russia to keep country together. Lost a war with Japan in 1905, followed by civil revolution. least industrially developed of alliance countries
Austria worried that Russia had a strong army and supported Serbia
Serbia and Russia close allies

Austria	Serbia
[redacted]	[redacted]
many ethnic groups, some wanting independence (particularly the Serbs in the south near Serbia)	[redacted]
Austria worried that Serbia was becoming powerful with a strong army.	Emerged as the strongest country in the Balkans by 1913
Serbia wanted to be able to defend Serbs in the region (in the Balkans area and in Austria) and didn't like Austria's aggression	

10 points	**Explanation of connections**
	cause and effect flow
10 points	(1 for no position. 2-3 for position without logical explanation from given data.
	4-5 for reasonable explanation from given data. 6-8 for good explanation from given data.
	9-10 for excellent and thorough justification)
	Explanation of responsibility
	Take a position
	Logically defend it