The Benefits of Immersion for Spatial Understanding of Complex Underground Cave Systems

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Abstract

A common reason for using immersive virtual environments (IVEs) in visualization is the hypothesis that IVEs should provide a higher level of spatial understanding for complex 3D structures, such as those found in underground cave systems. Therefore, we aimed to explore the use of IVEs for visualization of underground caves, and to determine the benefits of immersion for viewing such models. We ran an experiment in which domain experts answered questions with two different levels of immersion. The results show that for certain tasks the more immersive system significantly improved accuracy, speed, and comprehension over the non-immersive environment, and that 3D visualization overall is a good match for the underground cave data.

Categories and Subject Descriptors

I.3.7 [**Three-Dimensional Graphics & Realism**]: Virtual Reality

Keywords

Immersion, spatial understanding, visualization, cave

1. Introduction

Many researchers have proposed that immersive virtual environments (VEs) should provide a higher level of spatial understanding (e.g., Durlach & Mavor, 1995) because they support natural viewing of virtual objects and scenes, with more depth cues than are present in desktop systems. This idea has led to the belief that immersive virtual reality (VR) should be useful for the visualization of complex three-dimensional (3D) data. Unfortunately, there are few empirical studies that show significant benefits of immersion for spatial understanding. Without such results, developers are not able to predict which datasets would be worth visualizing in immersive VR.

The purpose of this research is to empirically study the benefits of immersion for spatial understanding in the visualization of underground cave systems. Underground cave systems can be very complex and irregular 3D structures, which cannot be easily visualized using traditional means. Cave cartographers use overhead plan view, cross sections, depth coloring, and 2D profiles to help describe cave structures. Cavers and surveyors must interpret and mentally visualize the cave's depth and passage orientation using these 2D maps. Unfortunately, 2D cave maps are not practical in places where upper levels hide lower levels and passage distinction can become difficult (Figure 1).

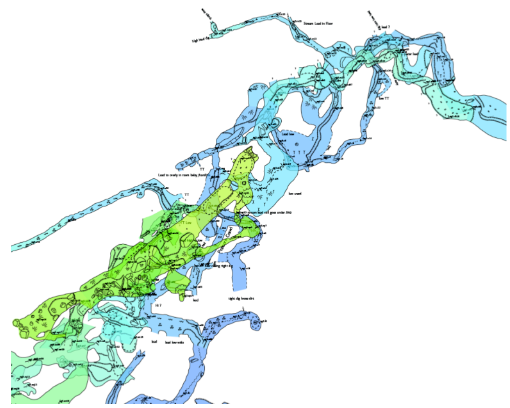

Figure 1: 2D cave map showing multiple stacked levels.

We have developed a 3D visualization of complex cave structures that can be viewed interactively in an immersive projection technologies display. Our approach was to evaluate the use of this system in two different modes with higher and lower levels of immersion. We hypothesized that the more immersive system will result in better spatial understanding and better performance.

We follow Slater (Slater, 2003) in his definition of immersion as the "objective level of fidelity of the sensory stimuli produced by a technological system." The level of immersion, in other words, is an aspect of the technology (not the user or the user's experience) that can be modified, controlled and used as an independent variable for empirical studies. We also note that immersion is not a single construct, but one that has many components, such as field of regard, field of view, stereoscopy, display size, display resolution, and head-based rendering.

2. Related Work

Research on the benefits of immersive VR can be classified into two categories. The first includes controlled studies investigating the effects of one or two components of immersion on user performance. For example, Arthur examined the effects of field of view in head-mounted displays (Arthur, 2000). Barfield et al. (Barfield *et al.*, 1997) studied head tracking and stereoscopy for its effects on spatial understanding of small 3D virtual objects (the same benefit we are seeking).

The other category of immersion research includes more practical, real-world comparisons of non-immersive and immersive VR systems. For instance, Arns and her colleagues compared desktop and CAVE-based versions of a statistical visualization tool and found advantages for the CAVE-based version for certain tasks (Arns *et al.*, 1999). Gruchalla (Gruchalla, 2004) performed a similar comparison for an oil well path planning applications and reported significant performance gains in the CAVE.

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Our experiment falls between these two categories. We control the experiment by using the same display, tracking, and input hardware in both conditions, and removing some of the components of immersion from one condition. However, we do not control the components of immersion individually, as we have in some prior work (e.g., McMahan *et al.*, 2006), because we wish to demonstrate a benefit of immersion in general before investigating further to determine which component(s) of immersion cause(s) the benefit.

3. System Design

Our major goal for the system was to design a visualization of complex cave systems that could be viewed interactively in an immersive VE. We will describe how we developed the models and the systems used to display the models.

3.1 Models and Cave Survey Data

Over four miles of cave survey data of Alva Blankenship Cave (ABC) and Blankenship Blowhole (BB) was collected by the VPI Cave Club in a four-year surveying project. Surveyors conduct a cave survey by taking measurements starting at the cave entrance. A compass/clinometer and a measuring tape are used to measure distance, azimuth, and inclination for each survey shot, and these measurements are used to create a 2D plan view sketch of a section of passage (Figure 2) as well as a 3D line plot of the cave.

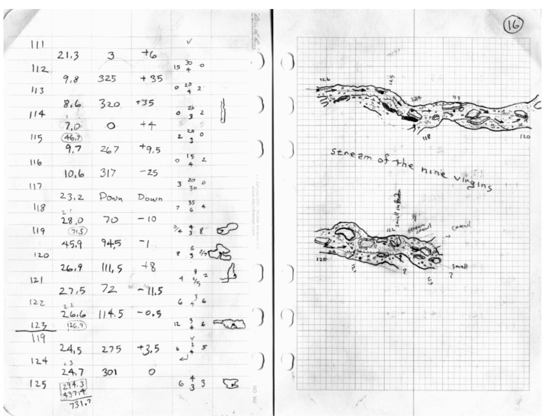

Figure 2: In-cave sketch of a section of Alva Blankenship Cave

To create the 3D models used in our work, we began by scanning, tracing, and connecting each section of the cave sketch. The 2D walls were then scaled, rotated, morphed and extruded into 3D. The 3D line plot determined inclination and direction of each section (Figure 3). We determined the ceiling height of the extruded 3D passage using passage width and manual specifications. Finally, digital USGS elevation maps were positioned over the 3D cave model, and an aerial photograph was draped over this terrain geometry.

The only way of verifying survey accuracy is by closing a loop of survey shots in the cave. Both ABC and BB have many loops which all have errors of less than 3%. Sketch morphing errors are also less than 3%. Both models give a good overall representation of the caves' structures.

ABC (surveyed to 3.06 miles) has numerous domes, pits and maze-like upper level development. BB (1.04 miles) has upper levels that are continuous and have only a couple of connections between them. Both BB and ABC have complex structures and are therefore good datasets for testing the benefits of immersion.

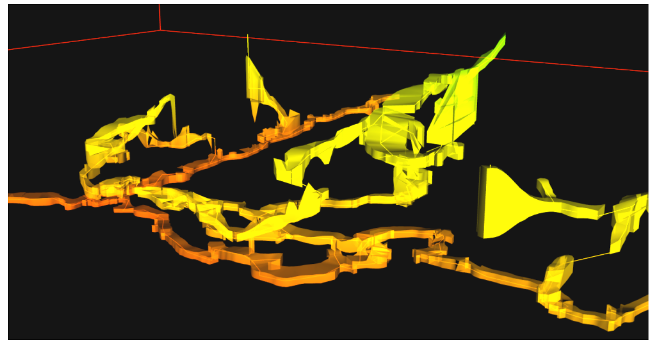

Figure 3: 3D model of a section of ABC. Colors indicate depth.

3.2 Apparatus

We used a four-screen Fakespace CAVE™ (yes, we are displaying caves in a CAVE!), which has left, right, front, and floor projection. An Intersense IS-900 tracker provided 6-DOF head and wand tracking In our study, a simple laser pointer was used to point objects out in the virtual environment. The cave visualization was rendered in real-time on five Linux PCs, using DIVERSE (Kelso *et al.*, 2002) software.

Figure 4: High immersion: four screens, stereo, head-tracked.

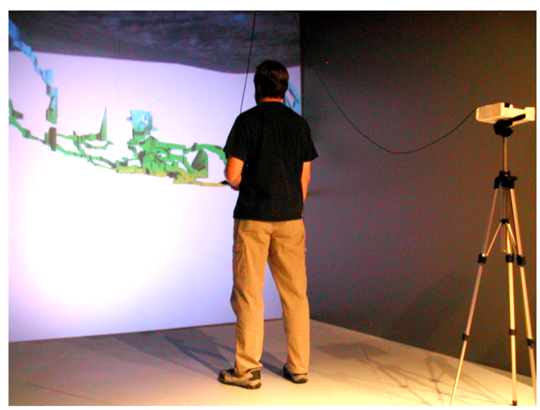

Figure 5: Low immersion: single non-stereo screen.

3.3 Levels of immersion

For our high level of immersion (figure 4), we used all four screens of the CAVE, stereoscopic imagery, head tracking, and the 6-DOF wand for navigation (users pointed in the direction of travel and pushed the joystick forward or backward to move, and pushed the joystick left or right to turn). The low level of immersion (figure 5) used only the front screen and the wand, with no stereo or head tracking (subjects in the low-immersion condition still wore the stereo glasses, in order to keep the brightness of the display constant). In terms of the components of immersion, then, these conditions differed in terms of stereoscopy (on or off), head-based rendering (on or off), and field of regard (270 degrees horizontal or 90 degrees horizontal).

4. Experiment

We ran a formal study to test our hypothesis that users will have better performance, indicating higher levels of spatial understanding, in the high-immersion condition.

4.1 Design and Procedure

Level of immersion (2 levels) and task (13 levels) were the two independent variables in our study. Both were within-subjects variables. Two different cave models (ABC and BB) were used, one in each level of immersion. Half of the subjects used ABC in the high-immersion condition, while the other half used BB in the high-immersion condition.

Task	Description	Task Type
1	Find highest point	Simple feature search
2	Find 2nd-highest point	Simple feature search
3	Find lowest point	Simple feature search
4	Identify three levels	Simple feature search
5	Identify connections	Detailed feature search
6	Find pits	Detailed feature search
7	Identify largest room	Relative measurement
8	Give water flow direction	Simple feature search
9	Measure stream dip angle	Absolute measurement
10	Measure stream dip angle	Absolute measurement
11	Find shortest path	Relative measurement
12	Measure passage to surface	Absolute measurement
13	Find surface location	3D projection

Table 1: Tasks used in the experiment.

Subjects were asked thirteen questions about each model (Table 1), and could physically or virtually navigate around the model. Dependent variables were the time taken to complete each trial and the accuracy (right or wrong) of the subject's answers.

For example, we asked subjects, "What is the shortest path through the cave between point A and point B?" (Table 1, Task 11). In another task, the subjects were asked to project locations on overlaying surface topography to a point in the cave (Table 1, Task 13). All tasks were drawn from commonly asked questions about complex caves. Each task was intended to be a measure of some component of the user's spatial understanding.

We gave participants a 10-minute training session in the high-immersion condition using a cave model that would not be used for the actual experiment. The session trained participants in navigation and pointing. Participants then performed thirteen tasks in each immersion condition, always using the BB model for the first set of trials and the ABC model for the second set of trials. The order of presentation of the levels of immersion was counterbalanced. After completing both sets of tasks, the subjects were interviewed with an exit survey.

4.2 Subjects

Twenty-four domain experts (cavers) with caving and surveying experience participated in the experiment. Six participants were female. None had any experience with immersive VEs. The minimum age of the participants was 18 years, the average age was approximately 36 years, and the maximum age was 54 years.

4.3 Results

We conducted a two-factor ANOVA for both time and accuracy data. Level of immersion was highly significant for both time ($F(1,598)=18.82$, $p<0.0001$) and accuracy ($F(1,598)=33.67$, $p<0.00001$) with the high-immersion condition significantly faster (avg. task completion time=15.78s) and more accurate (avg. error rate=15%) than the low-immersion condition (25.00s, 33%).

Task also had a significant effect on both time ($F(12,598)=13.79$, $p<0.00001$) and accuracy ($F(12,598)=16.35$, $p<0.00001$). In addition the interaction between level of immersion and task was also significant for both metrics (Time: $F(12,598)=2.17$, $p<0.02$, Accuracy: $F(12,598)=2.35$, $p<0.01$).

We used t-tests to perform pair-wise comparisons of the high-immersion and low-immersion conditions for each task. Figure 6 displays the average time for each task at each level of immersion. We found a significant difference between the high and low levels of immersion for tasks 5, 6, 7, and 11, with the high level of immersion better in each case. These were also the tasks with the highest overall average times, as the graph shows.

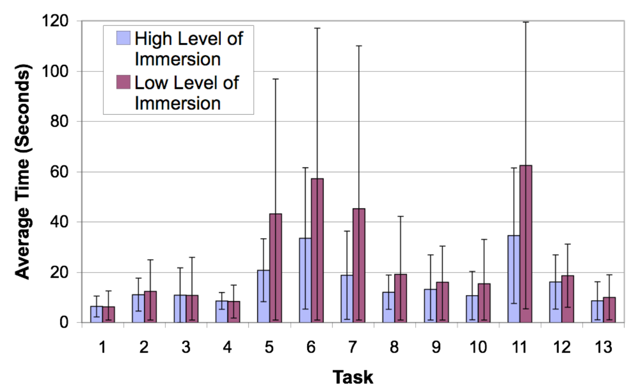

Figure 6: Average task performance time. Error bars represent standard deviation. Level of immersion is significant for tasks 5, 6, 7, and 11.

Figure 7 shows the error rate (percentage of tasks that resulted in error) for each combination of task and level of immersion. Tasks 2, 5, 6, 7, 8, and 11 resulted in a significant difference between the levels of immersion, with the high-immersion condition having significantly fewer errors in each case.

In our exit survey, we asked participants several questions about their impressions of the two levels of immersion.

First, subjects were asked to compare the usefulness of the high-immersion condition to other underground cave visualizations that they had used. Other cave visualizations include 2D cave maps, Survex (survex.com), Therion (therion.speleo.sk), and Compass (fountainware.com). Subjects rated the usefulness of our VE on a 5-point scale; where 5 represented much more useful than traditional tools. Subjects rated the high-immersion condition at 4.7 on average. One subject said, "Normally, I look at [2D] cave maps and I really don't understand what's going on. With the [highly immersive visualization], I really can understand the structure and passages." When asked the same question for the low-immersion condition, subjects rated it at 3.6 on average.

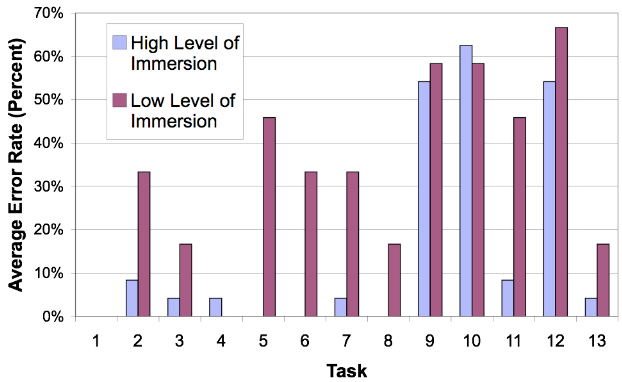

Figure 7: Error rate for each task at each level of immersion. Level of immersion is significant for tasks, 2, 5, 6, 7, 8, and 11.

96% of all subjects preferred the high level of immersion to the low level of immersion. One participant noted, "I can see where [passages] connect. This would be very useful to try to connect two caves or search for places to look for new passages." 91% of participants suggested that they would use the high-immersion system over a desktop system, if they had access to the facility.

4.4 Discussion of Specific Tasks

Overall, we found that the high-immersion condition improves performance and accuracy while completing common cave visualization tasks. However, these benefits were not consistent across all tasks.

Tasks 1, 2, 3, 4, and 8 asked the subjects to point out simple features (such as the highest point in the cave). We did not find a significant time difference between the two conditions for these tasks. Most of the subjects pointed directly to the features with little or no navigation. The error rate for tasks 2 and 8 was significantly higher in the low-immersion condition, probably because of the diminished depth cues and the lack of navigation. With the high level of immersion, subjects often used small head adjustments to locate the points.

In tasks 5 and 6, subjects searched for smaller, more detailed features. The high-immersion condition was significantly faster and more accurate (zero errors) for these complex tasks requiring an exhaustive search.

Tasks 7 and 11 dealt with comparative measurements in the cave. In both of these tasks, the high-immersion condition was significantly faster and more accurate. Participants were able to easily judge the relative sizes and distances in the model with the increased immersion, while participants often became lost or confused in the low level of immersion.

Tasks 9, 10, and 12, on the other hand, required absolute measurements. We found no significant differences due to level of immersion for these tasks. Subjects did not perform well in either condition, because they lacked a measuring device or scale.

Finally, in task 13 subjects had to identify a colored dot that was located directly over a specific piece of passage. In both environments, many subjects pointed directly to colored dots without investigating. Since this task lacked complexity, performance in both environments was similar.

5. Conclusions and Future Work

We evaluated a variety of tasks in an underground cave visualization system using two levels of immersion. We found that the high-immersion condition significantly improves accuracy and efficiency overall, and for some specific types of complex tasks requiring exhaustive search and/or accurate spatial judgments. Thus, higher levels of immersion have measurable benefits for spatial understanding, but not all spatial tasks require the additional immersion. Users also prefer the higher level of immersion and believe it to be more useful.

A VR system with a high level of immersion could provide similar benefits for other visualizations with complex irregular 3D datasets, such as geological systems, biological systems, and weather simulations, among others.

We did not design this study to determine which components of immersion caused the significant differences between the conditions. In the future, we plan to run a more controlled study that will investigate each component of immersion individually and in combination. This would allow us to predict the performance of other VR systems on similar tasks.

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