# The Impact of Immersive Virtual Reality Displays on the Understanding of Data Visualization

Ahmed Bayyari
Department of Applied Science
University of Arkansas at Little Rock
Little Rock, AR 72204, USA
akbayyari1@ualr.edu

M. Eduard Tudoreanu
Department of Information Science
University of Arkansas at Little Rock
Little Rock, AR 72204, USA
metudoreanu@ualr.edu

## ABSTRACT
This paper presents evidence that situational awareness in a visualization of data benefits from immersive, virtual reality display technology because such displays appear to support better understanding of the visual information. Our study was designed to de-emphasize perceptual and interaction characteristics of the displays and found that the task of counting targets is strongly influenced by the type of system used to render the visualization. Immersive-type displays outperformed traditional monitors. The target objects in the study have distinguishing features that cannot be identified from a distance to alleviate the effect of perceptual differences among displays. Counting was chosen because it entails basic understanding of the relationship among the data values in order to recognize previously counted items. The display choices consisted of a traditional monitor and three configurations of an immersive, projection environment, obtained by selectively turning off one or two projectors of a three-wall CAVE.

## Categories and Subject Descriptors
H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems—artificial, augmented, and virtual realities; I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism—virtual reality

## General Terms: Human Factors, Design, Experimentation

## Keywords: Virtual reality, immersion, information visualization, evaluation

## 1. INTRODUCTION
This paper evaluates the use of immersive VR approaches to aid in the understanding and taking advantage of a visualization of data, which is closely related to situational awareness in a visualization. The work concentrates on the benefits to the user that are brought by the merging of two fields: immersive VR and data visualization. VR seeks to make the viewer feel and experience various worlds. Data visualization focuses mostly on graphical and interaction techniques that allow a viewer to gain insight into abstract information. Such representations fall under two closely related areas: information visualization and scientific visualization. Although our interest is in information visualization, the manner in which the study was designed is also applicable to scientific visualization. For clarity, virtual reality (VR) in this paper refers to an immersive virtual environment that adjusts the user's point of view by tracking the head or hand.

The world shown via all displays is a composition of VR techniques aimed at making the world "feel" real and of an information visualization space consisting of both micro details, and macro context. One set of VR techniques include the addition of sky and background images to complement and blend with the 3D surface rendering of the data because previous research [1] suggests that the sense of presence is increased by real-looking landscapes. The other set of VR techniques are the addition of orientation objects and cues to increase the ability of the participants in the study to navigate and orient themselves in the virtual world [5]. We spent effort to ensure that there are enough orientation cues to reduce more pronounced orientation problems observed on non-immersive displays. The data visualization side of the virtual world consisted of random data that appeared as a 3D surface and as objects whose placement, shape, and texture were dependent on the underlying (random) data. This setup has the advantage that it shows both the details and the overall organization of the data in the same picture. The 3D surface provided the context, while individual object texture supplied the details of the data. In a visualization of real data, the texture could encode two additional variables (dimensions). The manner of providing both context and detail is the subject of intensive research in the information visualization community because most real-world datasets have multiple levels of detail and aggregation.

We conducted experiments using four settings in which participants were tested on a regular desktop monitor fitted with a hand-tracked interaction device (Desktop VR) and a varying number of CAVE screens. Our overall results showed that all participants scored higher using a CAVE over Desktop VR.

## 2. RELATED WORK
**Situational awareness** An area of psychology that is beginning to be applied to information visualization [9] is situational awareness because the visualization is not important on its own but only as a means of taking advantage of the underlying data in order to achieve the current goal of the user. Endsley [10] identifies three levels of situational awareness that can be applied to visualization as follow: 1) perception of the data elements; represented by a task such as searching; 2) comprehension of the data; understanding relevant existing relationships; and 3) projection of the future status; predicting where the next data point of interest is.

We chose the task of counting the number of times certain information appeared primarily because it exposes the participants in the study to the first and second levels of situational awareness. Counting requires the subjects to understand enough of the relationships among the data points to be able to determine what tar-


*VRST'06*, November 1-3, 2006, Limassol, Cyprus.

get objects have been already counted. Counting is only similar to searching in that it requires viewers to navigate and identify detailed information. Counting also has the built-in assumption that the viewer searches the entire visualization space, the global context. Searching may be too basic a task for information or scientific visualization because it allows the users to forgo understanding the global context and quit once the target piece of information is found. A third-level task may be the recognition of the global patterns, such as crop circles, formed by the target objects, where the user can predict where the next item resides.

**Information visualization** There is little research in information visualization that focuses on the effectiveness of the display methods. Notable exceptions are studies conducted by Ware and Frank [6] on 3D visualizations of networks (graphs) in which a fish tank VR display was deemed more beneficial to users than traditional monitors. Arthur *et al.* [7] also considered the fish tank with a representation of trees among other tasks and found that the tank improved user performance. That type of display employs stereo and head-tracking, but it cannot be categorized as immersive. Moreover, the graph and tree data in those studies are quite different than the micro-macro type of data and representations in our experiment. Polys *et al.* [13] compared depth cues and associations of Information Rich Virtual Environments for a tiled display and regular monitor. No data about the immersive, three-wall VR was gathered in their study.

We employed focus+context approaches that rely on the 3D characteristics of the human vision to produce "natural" visualizations in which the space closer to the observer shows details and space farther away conveys context. The visualization employed in our experiment is fully 3D because the goal was to merge VR into information visualization. However, in the information visualization community the choice between 2D and 3D is not clear-cut. There are conflicting results that support both sides of the debate of whether 3D rendering commands better performance. Levy *et al.* [8], for example, found that 3D is not beneficial for users interpreting business charts, while Ware and Franck [6] suggest that 3D graphs improve user performance.

**Virtual reality** Several researchers have set out to bring empirical proof of the benefits of using an egocentric setting using VR over the exocentric view provided by traditional monitors. The studies mentioned next differ from this paper in that they either used searching or required manipulation of the virtual world as well as did not emphasize comprehension of the data.

Pausch *et al.* [4] and Robertson *et al.* [3] had all conducted similar research and found that users performed better using HMD than regular desktop interfaces, and that Desktop VR was superior to HMD for a simple search task. Schulze *et al.* [12] concluded that Fish Tank VR of a scientific visualization was superior to CAVE when the task is "dominated by visual search". No navigation was required in their experiment because the whole visualization was visible at once, although extensive manipulation of the world was likely required. Swan *et al.* [2] evaluated user performance for searching, navigation and map manipulation in a virtual environment and reported that users performed better using the desktop setting over CAVE.

Other studies, such as Demiralp *et al.*[11], only collected subjective data from domain experts about higher –level tasks, and cannot be easily compared to our measurements. Demiralp, however, compared the characteristics of CAVE and Fish Tank systems (size, resolution, brightness) and reported that most users preferred desktop VR because the image was crisper and brighter, which allowed better perception.

Our study, as discussed earlier, differs fundamentally from previous research in that it requires participants to navigate the entire virtual world to count the number of target objects without over- or under-counting. This requires level-two situational awareness which adds an extra level of complexity. The virtual world we used was significantly larger and allowed users more movement freedom by not pinning them down in a fixed location or restricting their travel. Our experiment was also designed to depend only on simple navigation commonly found in both types of VR. Another notable difference is that our results were objective and only empirical data was collected without factoring in the opinions of the subjects. Our measurements exceeded 800 data points, which is quite a large number compared to the other studies mentioned here.

# 3. EXPERIMENT

The study strived to reduce known factors (i.e. screen size, resolution, etc.) that affect participants and put traditional monitors at a disadvantage relative to immersive VR. The size of the world was chosen large enough to overwhelm even the larger size and total pixel count of the immersive CAVE, so that the task of counting data is not trivial in any display setting. We also wanted to limit interaction given the difficult and untested nature of current VR interaction methods, especially immersive interactivity. Navigation is a simple technique common to both desktop and immersive systems, which benefits both alike.

## 3.1 Materials

The software for the virtual world was implemented using C++ and OpenGL. A specialized library, CAVELib, for handling immersive displays and the interaction devices associated with them was utilized to create a seamless application capable of running in all display set-ups.

Participants underwent a PowerPoint presentation with all the necessary instructions to complete the study. During each session, participants received a paper scoring sheet for that particular session Each sheet had 17 lines corresponding to 17 trials, and each line contained numbers from 1 to 15 (maximum number of target objects per trial).

**Three sessions were conducted inside of a CAVE** that included three screens, all powered by DLP projectors in a front-right-floor configuration. The projectors were bright enough to operate with regular fluorescent lights on, although we used soft incandescent lighting. The size of each image was 10'x8' at 1280x1024 resolution @ 96 Hz. The front and right images were back-projected, and the floor's length aligned with the front screen. Each screen was controlled by its own Intel Pentium 3GHz dual processor personal computer with 1GB RAM and running Windows XP. A pair of 3D stereo shutter glasses was needed for the immersion sensation and an Ascension Flock-of-Birds © tracker device mounted on these glasses enabled tracking of the user's head position. The wand, a NeoWand©, was also tracked. A chair was placed on the floor screen, but the choice of sitting or standing was left at the user's discretion. There is no large seam between the three screens. Moreover, the screens are color-balanced to make the seams even less apparent.

We performed a small informal pilot study and noticed among other things that the accuracy did not seem to change with the floor turned off. The more interesting research question became how much of a penalty having the floor on and the right screen off would be. Therefore, the 2-wall configuration was chosen to be front and floor screens.

**The monitor sessions** used a 19" desktop screen with a slightly different wand, Wanda©, and an Ascension Flock-of-Birds tracker device attached to the wand. The display was monoscopic with a resolution of 1280x1024 pixels. The UP and DOWN arrows on the keyboard were used as means for the user to gaze up and down. The arrow keys were needed to allow the user to control the azimuth to inspect the slope of a mountain or valley. Actual hand positions were translated to virtual hand coordinates to allow users to hold the wand at a comfortable position with respect to the screen to minimize arm fatigue.

## 3.2 Subjects

A total of 13 college students volunteered to participate in the study which offered cash payments for their time and effort. Three grand cash prizes were offered to the people that scored the most accurate results with the time being the tiebreaker. Accuracy was measured by how close the participant's responses were to the correct answers regardless of completion time.

## 3.3 Design

The independent variables where TRIAL_NUMBER (17 trials, each with different data to be displayed), and DISPLAY_TYPE (monitor, one-wall, two-wall, three-wall). The study required participants to go through all trials and all display types to collect 68 data points per participant. The display types where presented in a random order to each participant. The dependent variable was ABSOLUTE_ERROR, which quantified the number of objects under- or over-counted by the participant.

## 3.4 Procedure

The study was divided into four different sessions of 17 trials. Each trial ran for a maximum of two minutes, but could be ended early by the user.

The study was divided into four sessions: 1) desktop monitor, 2) One-wall (front screen of a CAVE), 3) two-wall (front and bottom screens), and 4) three-wall (front, right, and bottom screens) configurations. The latter provided the most immersion in our virtual reality lab. The different wall configurations utilized the same CAVE environment while muting (shutter on) unwanted screens depending on the selected session. Each trial had a unique randomly generated surface creating a base landscape. Some landscapes were harder to navigate than others depending on the random seed and noise level that were used to generate the underlying data. Each trial contained 15 objects that were randomly selected and textured simulating more detailed information (two additional dimensions could be presented *in lieu* of texture in an actual visualization). Each object was clearly displayed in full on top of the terrain surface and within environment boundaries. Only three object shapes (cylinder, sphere, and disk) and three textures (Figures 2) were available. The program guaranteed that at least one of each object and texture was present. Screen resolution was irrelevant because the objects were relatively large and easily visible when the user was within a few virtual feet from the object.

Corresponding trial numbers in each session had the same set of randomly generated landscapes, objects, and textures (i.e. 1$^{st}$ trial in session 1 was identical to 1$^{st}$ trial in session 2, etc). However, participants were not aware of this fact. This alleviates randomness and improves the comparison of the results for the n-th trial under different display conditions and users. To keep the study from being biased towards one starting session or another, the order of the sessions was varied among participants using a factorial scheme (i.e. no two participants took the same sessions in the same sequence).

Each trial began with the user starting at the same corner at the edge of the virtual world to avoid the disorientation associated with unfamiliar places [5]. The program stopped automatically between trials to allow users to mark the number of target objects found on the answer sheet. All trials were self-paced and controlled by using the wand in two ways: pressing the left button paused/resumed an ongoing trial or started a new one after the current trial was completed; and pressing the left and right buttons together ended an active trial.

A timer and a compass were placed in the top left corner and top right corner, respectively, to assist users in keeping track of time and heading in the virtual world. And since previous research suggested that participants take advantage of environmental cues to assist in performing an exhaustive search, four distinct tall columns were placed in each corner of the world to enhance orientation and awareness of visited/non-visited areas. At least one column was visible from any place in the virtual world. Mountains of various heights surrounded the terrain to increase situational awareness. An illustration of the environment is shown in Figure 1.

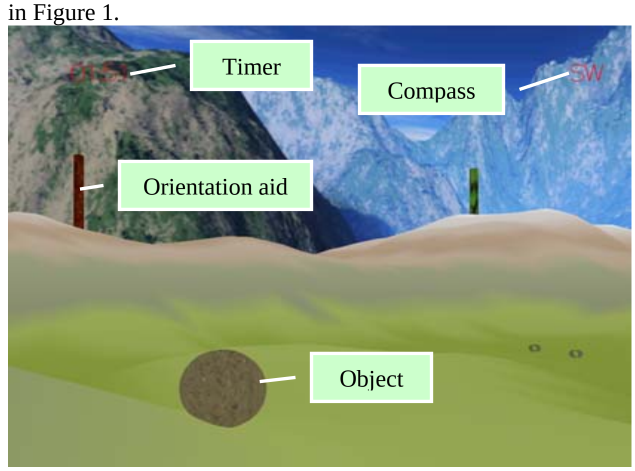


**Figure 1 Virtual world screenshot. Notice background picture blends in with foreground visualization surface.**

The main surface creating the landscape was based on randomly generated data consisting of intensities for a 2D grid which were mapped to the height and color of the 3D surface. Perlin noise was utilized by the designers to tune the roughness of the landscape.

The objective was to find and count all textured objects that contained pebbles as shown in the middle swatch in Figure 2 without regard to the object's shape. Textures looked very similar to each other in the virtual environment when viewed from a distance and were purposefully selected in this manner to force users to move close to the objects to identify their textures. Furthermore, counting the target became harder in rugged terrain containing rough highs and lows.

**Figure 2 The image in the center is the target texture**

# 4. RESULTS

A total of 221 data points was collected for each display type. The average absolute error for each display type is shown in Table 1. Overall, the monitor has the highest error rate, and the three-wall VR fostered the most accurate answers. All types of VR are superior to the monitor. There were on average 5.35 target objects in the 17 trials, and the number of such objects may have strongly affected the error rate. Considering the average number of targets, monitor displays had a counting error rate of 40% of total targets, while three-wall VR had a rate of 28%. That computes to about 43% more errors for a monitor session than for the three-wall one.

There is a slight increase in error rate for two screens versus one screen VR. About 70% of the participants performed better during the one-wall session than during the two-wall.

**Table 1 Average of ABSOLUTE_ERROR**

| DISPLAY_TYPE | Total |
|---|---|
| Monitor | 2.12 |
| One | 1.67 |
| Two | 1.72 |
| Three | 1.48 |
| Grand Total | 1.75 |

An analysis of variation shows that DISPLAY_TYPE is a significant factor for the error rate ($F_{3, 36}$=15.17, p<.0001). The trial number is also statistically significant, which suggests that the underlying data being presented has an impact on the manner in which people gain insight into information. Some values of the data are easier to understand than others.

We also performed an analysis on the VR-only sessions and found a significant difference for the display type ($F_{2, 24}$=5.45 p=0.0112). This shows that different types of immersive displays have different impact on the user's accuracy. An analysis focusing only on one and two walls found no statistically significant difference between the two display types.

There is no obvious transfer of experience between the four sessions as captured by the data. Table 1 presents the average absolute error for each type of display broken down by the order in which each session appeared. Also, the order in which the trials were presented did not make a difference in that later trials do not get better than the first ones. The underlying (random) data presented in each trial makes that trial easier or more difficult.

## 5. DISCUSSION

We draw the conclusion that immersive displays support better understanding of data because (a) our results show that the 3-wall display is clearly superior to desktop visualization; and (b) perceptual aspects of the counting task favor desktop VR in that:
(1) monitors have a clearer, crisper image as evaluated by users of scientific visualization [11], which should have allowed the textures of our target objects to be more readily observed on a monitor; and (2) simple searching is shown to be more accurately performed on desktop VR by previous work (Robertson *et al.*[3], Schulze et al.[12], and map-based searching [2]). The map-based study is close to ours in the appearance of the virtual world, and found that people identify text faster on a desktop monitor. Due to the trade-off between speed and accuracy, it is likely that, if the time were fixed, the people in the map-based study would have been more accurate on the desktop.

Therefore, although our experiment favored perceptual features of the desktop VR, immersive displays outperformed the desktop system and one probable explanation is that immersive environments support better comprehension of the visualization.

Information visualization can benefit from employing immersive displays, which is in line with previous research on VR and its usefulness to other types of tasks such as navigation, presence, or memorization [3][4]. Our results show that the accuracy of the users in VR, given a fix duration, is significantly improved for a task related to information understanding.

Although we could not find a statistical difference between one and two walls, it is probably incorrect to conclude that larger displays, with higher resolution are the same as smaller ones. The study was designed to measure the weaker of the two possible configurations of a three wall CAVE, the front+floor combination. Our pilot study provided the feeling that the front+right combination of screens was not much different than the full 3-wall. Further research is needed into this subject.

Immersive displays suffer as much as the computer monitor from variations in user performance from a trial to the next. The study found that the input data has a significant impact on performance regardless of the display system. For a designer, this is an undesirable characteristic because none of the four types of display offer consistent, predictable performance for a range of input data.

## REFERENCES


[1] Slater, M., Linakis, V., Usoh, M., Kooper, R. Immersion, Presence, and Performance in Virtual Environments: An Experiment with Tri-Dimensional Chess. Department of Computer Science, University College of London, London, UK.

[2] J. Edward Swan II, Joseph L. Gabbard, Deborah Hix, Robert S. Schulman, Keun Pyo Kim, "A Comparative Study of User Performance in a Map-Based Virtual Environment," p. 259, IEEE Virtual Reality Conference 2003 (VR'03), 2003.

[3] Robertson, G., Czerwinski, M., and Dantzich, M. Immersion in Desktop Virtual Reality. Microsoft Research. One Microsoft Way. Redmond, WA 98052, USA.

[4] Pausch, R., Proffitt, D., and Williams, G. Quantifying Immersion in Virtual Reality. University of Virginia.

[5] Baker, M. P., Wickens, C. D. Human Factors in Virtual Environments for the Visual Analysis of Scientific Data. National Center for Supercomputing Applications. University of Illinois.

[6] Ware C. and Frank G. Evaluating Stereo and Motion Cues for Visualizing Information Nets in Three Dimensions. ACM Transactions on Graphics, 15(2), p.121-139.

[7] Arthur K. W., Booth K. S., Ware C. Evaluating 3D Task Performance for Fish Tank Virtual Worlds. ACM Transactions on Information Systems, Vol. 11, No. 3, July 1993, p. 239-265.

[8] Levy E., Zacks J., Tversky B, Schiano D. (1996) Gratuitous Graphics? Putting Preference in Perspective. Proceedings of CHI 96, p. 42-49

[9] Livnat, Y.; Agutter, J.; Shaun Moon; Foresti, S., "Visual correlation for situational awareness," Information Visualization, 2005. INFOVIS 2005. IEEE Symposium on , vol., no.pp. 95- 102, 23-25 Oct. 2005

[10] Endsley M. R., Bolte B., Jones D. G. (2003) Designing for Situation Awareness: An Approach to User-Centered Design, Taylor & Francis

[11] Demiralp, C. Laidlaw, D. Jackson, C., Keefe, D. Zhang, S. Subjective Usefulness of CAVE and Fish Tank VR Display Systems for a Scientific Visualization Application. Computer Science Department. Brown University. Providence, RI

[12] Schulze, J.P., Forsberg, A.S., Kleppe, A., Zeleznik, R.C.,Laidlaw, D.H. (2005). Characterizing the Effect of Level of Immersion on a 3D Marking Task. Proceedings of HCI International, Las Vegas.

[13] Polys, N. F., Kim, S., and Bowman, D. A. 2005. Effects of information layout, screen size, and field of view on user performance in information-rich virtual environments. In Proceedings of the ACM Symposium on Virtual Reality Software and Technology (Monterey, CA, USA, November 07 - 09, 2005). VRST '05. ACM Press, New York, NY, 46-55.