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R. Boulic, C. Cruz Neira, K. Kiyokawa, and D. Roberts (Editors)

Trade-Offs Related to Travel Techniques and Level of Display Fidelity in Virtual Data-Analysis Environments

E. D. Ragan,[1] A. Wood,[1] R. P. McMahan,[2] and D. A. Bowman[1]

[1]Department of Computer Science, Virginia Tech, US
[2] Department of Computer Science, University of Texas at Dallas, US

Abstract

Because effective navigation in 3D virtual environments (VEs) depends on the specifics of the travel techniques and the display system, we compared two travel techniques (steering and target-based) and two display conditions—a high-fidelity setup (a four-wall display with stereo and head-tracking) and a lower-fidelity setup (a single wall display without stereo or head-tracking). In a controlled experiment, we measured performance on travel-intensive data analysis tasks in a complex underground cave environment. The results suggest that steering may be better suited for high-fidelity immersive VEs, and target-based navigation may offer advantages for less immersive systems. The study also showed significantly worse simulator sickness with higher display fidelity, with an interaction trend suggesting that this effect was intensified by steering.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Computer Graphics]: Multimedia Information Systems—artificial, augmented, and virtual realities

1. Introduction

Navigation is often an essential element of virtual environments (VEs), especially for those based in large or complex spaces. Ideally, users should be able to focus on their primary tasks in the VE, but traveling through 3D environments can be difficult [Say04], particularly when natural locomotion is not available due to technological and space limitations. *Steering* travel techniques are commonly used to allow continuous control of the direction of movement [BKLP05]. Though it is generally easy to understand [Min95], steering requires practice (e.g., [RPJ97]), can be slow for long distances (e.g., [BDHB99]), and can cause disorientation (e.g., [Say04]). An alternative travel metaphor is *target-based travel*, in which the user indicates a specific location and the system moves the user to that location [BKLP05].

Additionally, the effectiveness of travel techniques can depend on the display system itself, since the features of immersive VEs can affect the travel technique and navigation decisions [ETT08]. To describe differences in VE systems, we use the term *display fidelity* to refer to the objective level of sensory fidelity provided by a system [MBZB12]. Though prior research indicates that target-based travel may be better than steering for some immersive applications (e.g., [ZLAFK02]), we predict that this may not be true for many other types of applications.

In order to obtain a better understanding of the relationship between virtual reality (VR) systems and travel techniques, we conducted a study comparing a target-based travel technique to a pointing-based steering technique in two contrasting levels of fidelity using a four-sided CAVE-like display. For the context of our experiment, we needed a task that required significant navigation. We implemented a data-exploration environment based on an underground cave, with supplemental visual information presented throughout the environment. In our study, participants completed two types of data analysis tasks: searching and determining data relationships. Results show that steering in a high-fidelity setup allows for faster data analysis, but at the cost of increased frustration and simulator sickness.

2. Experiment

We expected steering to allow better performance in the high-fidelity condition and the target-based technique to be better in the low-fidelity condition for data analysis tasks. As our VE was a complex cave with intersecting passageways and elevation changes, we hypothesized that the addi-

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tional display surfaces available in the high-fidelity condition would make it easier to take advantage of the increased level of control provided by steering.

We also hypothesized that participants would perform better in the high-fidelity conditions. As previous studies have shown that physical view rotation helped users to learn spatial layouts and effectively navigate 3D spaces [CGBL98, RPJ99]. In addition, we expected head tracking to help participants to more easily view around corners and obstructions. 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 [WAB93].

This experiment was conducted using a VisBox VisCube, a surround-screen CAVE-like display composed of three rear-projected display walls and a top-projected floor, each supporting passive stereo. In the low-fidelity conditions, participants wore blinder glasses to match the field of view to that of the stereo glasses. An Intersense IS-900 motion tracking system was used to enable head tracking in the high-fidelity conditions. Both navigation techniques used a tracked wireless wand. The experiment followed a 2x2 between-subjects design for display fidelity and travel technique, resulting in four conditions. The high-fidelity condition had stereo and head tracking, and used all four display screens. The low-fidelity condition used only the front display screen without head tracking or stereo.

For travel, the steering technique allowed users to control exact positional movements, as well as rotation. Participants controlled translation by physically pointing the wand in the direction of travel and moving the wand's joystick forward or backward. Rate-controlled rotation around the vertical axis was controlled by moving the joystick to the left or right. With the target-based technique, participants could still control rotation with the joystick. However, rather than having the ability to move to any position, participants could only move to pre-placed waypoint locations. With this technique, the VE contained 19 waypoints, represented by large checkered cubes (see Figure 1, bottom). Participants could select an adjacent waypoint by selecting the marker (via cone-casting) and pressing a dedicated wand button. This would automatically and smoothly transition the participant to the selected waypoint through interpolation.

2.1. Task

The experiment environment was designed to resemble an underground cave with branching passageways of open chambers of various sizes. Since elevation varied throughout the cave environment, full 3D travel was required to reach all areas. The VE was textured with a rocky texture. In addition to the cave geometry, 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.

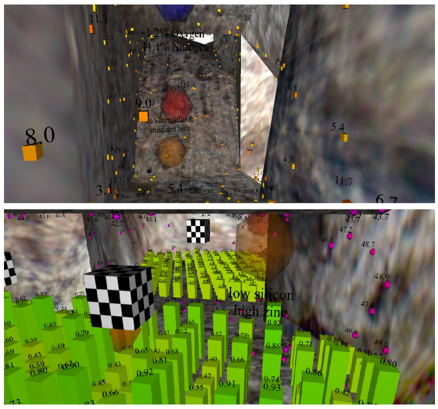

Figure 1: *Two views from within the information-rich cave*

Temperature values and *iron* content were both presented via sparse point clouds that lined the surfaces of the cave. Each point was colored along a gradient according to data value. Temperature data used spherical data points with color ranging from blue to red, while iron used small cubic points colored from yellow to red. Next, *sub-surface depth*, relating to the density of the rock under the surface, was presented on areas of the cave floor using 3D bars with heights proportional to values. All data points and bars included labels with their specific numerical values. Additionally, several large, partially transparent 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 billboarded text. Blue markers presented *gas concentrations* with numerical percentages for oxygen and nitrogen content. Orange markers presented *mineral concentrations* with labels showing textual indicators of the relative levels of zinc and silicon (e.g., "very low," "high"). As navigation landmarks, red area markers had alphabetic labels corresponding to locations in the cave.

Each group (temperature, iron, sub-surface depth, and area markers) 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.

The first task was a search task. Participants were asked to find either the absolute highest or lowest data point for a given data type. To encourage fast responses, participants were allowed multiple guesses. Participants were allowed to continue guessing until the time limit (five minutes) was reached. 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.

A correctness score was calculated as the total correct answers (i.e., correct area name and value). Also, a time score was calculated by summing the amounts of time taken to correctly answer all questions. If the participant did not correctly answer a question within the five-minute time limit, a penalty of ten minutes was instead added to the time score.

Participants were also asked to remember the areas where they found the extreme values and the corresponding data type while completing the search task. A post-task test asked questions about which areas had these extreme values and included a top-down map with the area letters labeled. The sum of correct answers for this test served as a metric related to mental workload and the effectiveness of the condition.

For the second task, participants were asked to compare two data types and decide if and how the data values were related throughout the entire cave. Three relationship types were possible: direct, inverse, or no relationship.

This task included six questions, each with a four-minute time limit. Only one answer was allowed per question, and the experimenter provided the correct answer after the guess. A correctness score was calculated as the sum of correctly answered questions, and total time was the sum of times taken to answer the questions. Similar to the memory component of the search task, participants were also asked to remember the correct relationships for all questions. A memory score was calculated as the total correct responses.

2.2. Participants

A total of 39 participants (22 male) were recruited (ages ranging from 19 to 53, median 24). Participants were balanced across conditions by both gender and self-reported levels of experience with data analysis and scientific visualization. Seven participants had to withdraw due to simulator sickness. Of those seven, six were females, and five were in the condition with high fidelity with steering. The remaining 32 participants were balanced across the four conditions by gender and experience.

2.2.1. Search and Relationship Task Results

An independent factorial ANOVA for effects of travel technique and fidelity on search correctness score found a significant effect of display 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 (M = 4.63, SD = 0.81). The test failed to find an effect due to travel and found no interaction between travel technique and fidelity. The ANOVA for time scores failed to detect 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 fidelity conditions had faster times (M = 1105s, SD = 548) than the high fidelity (M = 1392s, SD = 421), and steering had faster times (M = 1132s, SD = 531) than target-based travel (M = 1365s, SD = 458).

An ANOVA for effects of travel technique and display fidelity on relationship correctness failed to find significant effects for travel technique or fidelity, and no interaction was detected. For total task time, we 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 = 696s, SD = 218) than with the target-based technique (M = 879s, SD = 239). No significant effect on task time was found for the level of display fidelity and no significant interaction was found.

For post-search memory, the ANOVA found a significant interaction between travel technique and fidelity for the search task, with $F(1, 28) = 5.46$ and $p = 0.03$. A post-hoc Student's t-test indicated that the condition with high fidelity and steering was significantly better than the condition with low-fidelity and steering. 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. This interaction suggests that steering may be better suited for high-fidelity VEs, and target-based travel may offer advantages for less immersive systems. The test failed to find significant effects for memory scores for the relationship task.

2.2.2. Simulator Sickness Results

Though analysis of the effects of travel technique and display properties only considered the 32 participants who completed the entire experiment (all questions from both tasks), the seven participants who stopped the study early due to sickness were also considered for the simulator sickness effects. Each participant was given a simple simulator sickness rating from zero to three. A zero rating was given for no reported discomfort. A rating of one was given for minor headache or eye strain. A rating of two was given for a high level of discomfort (e.g., nausea or more severe headache). A rating of three was given for participants with sickness levels so high that they did not finish the study.

We tested for effects of travel and display fidelity on sickness with two-way ordinal logistic regression. The likelihood ratio test indicated a significant effect of fidelity, with $\chi^2 = 7.34$ and $p < 0.01$. The test found no significant effect of travel techniques. It also failed to find a significant interaction between travel and fidelity, with $\chi^2 = 2.18$ and $p = 0.14$. However, we suspect that the interaction could have been significant with more participants. Figure 2 shows this interaction. Between the two high-fidelity conditions, sickness was worse with steering, though travel technique did not seem to affect sickness levels with low-fidelity. We hypothesize that the additional movements allowed by unrestricted manual control (especially elevation changes and swerving/jagged movement) 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 sick-

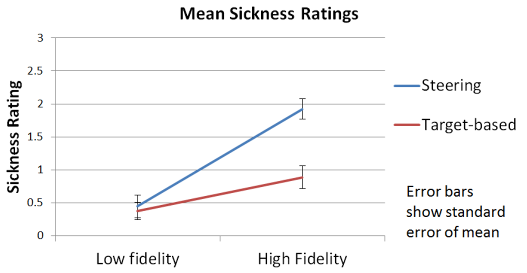

Figure 2: *Interaction between travel and display fidelity for simulator sickness*

ness, with R = 0.38 and p = 0.02. Since multiple females in the condition with high fidelity and the steering technique got sick and stopped early, gender was not balanced for the analysis of sickness effects. Thus, while females did experience worse sickness overall, this could have been a side effect of the higher fidelity.

Relating to the task performance, the sickness effects could explain the significant search performance detriment due to higher fidelity. For 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 with worse sickness did tend to earn lower search scores (though not significantly).

3. Discussion

While many controlled studies have found evidence of the potential benefits of immersive VEs for a variety of tasks, our results show that these effects depend on other factors beyond display features. Our results for the search task show that performance 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 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 advanced display components. Discomfort may have been worsened by the jagged-edged walls, irregular pathways, dips, and inclines. Multiple participants reported that the changes in elevation were the most unsettling (in the high-fidelity conditions with the projected floor, some participants even stumbled in reaction to elevation changes).

As for the travel techniques, the higher degree of navigational control afforded by steering did allow faster performance in the data-relationship task. Steering helped participants to more-easily scan areas continuously, 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. We suspect that this was because steering allowed both translation and rotation simultaneously, and allowed participants to make harsh movements and create more jarring visual experiences. The significant interaction between travel and 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.

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.

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