A Comparison of Immersive HMD, Fish Tank VR and Fish Tank with Haptics Displays for Volume Visualization

Wen Qi*
Eindhoven University of Technology

Russell M. Taylor II
UNC Chapel Hill

Christopher G. Healey
North Carolina State University

Jean-Bernard Martens
Eindhoven University of Technology

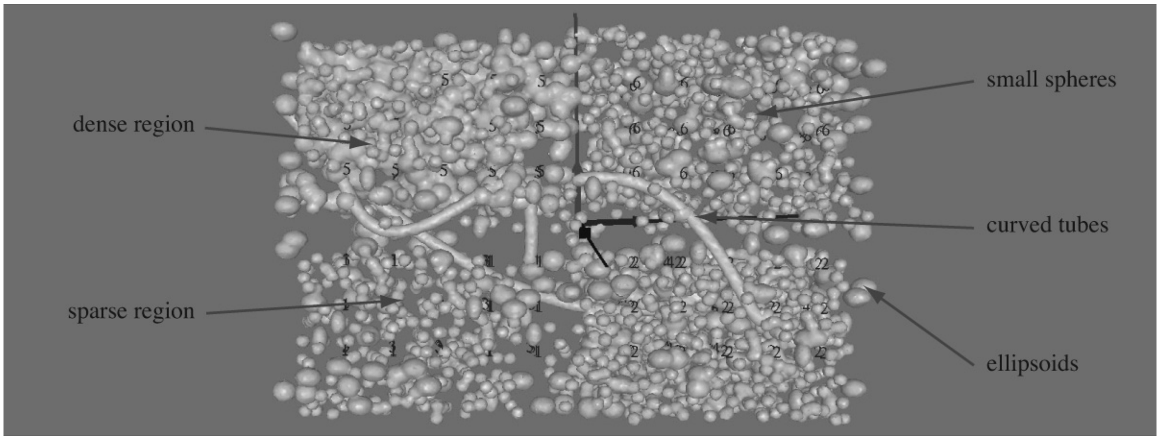

Figure 1: An example trial from our experiment, showing a top-down view on a simulated volume with different experiment conditions like shape, size, density, and connectivity highlighted

Abstract

Although a wide range of virtual reality (VR) systems are in use, there are few guidelines to help system and application developers select the components most appropriate for the domain problem they are investigating. Using the results of an empirical study, we developed such guidelines for the choice of display environment for four specific, but common, volume visualization problems: identification and judgment of the size, shape, density, and connectivity of objects present in a volume. These tasks are derived from questions being asked by collaborators studying Cystic Fibrosis (CF). We compared user performance in three different stereo VR systems: (1) head-mounted display (HMD); (2) fish tank VR (fish tank); and (3) fish tank VR augmented with a haptic device (haptic). HMD participants were placed "inside" the volume and walked within it to explore its structure. Fish tank and haptic participants saw the entire volume on-screen and rotated it to view it from different perspectives. Response time and accuracy were used to measure performance. Results showed that the fish tank and haptic groups were significantly more accurate at judging the shape, density, and connectivity of objects and completed the tasks significantly faster than the HMD group. Although the fish tank group was itself significantly faster than the haptic group, there were no statistical differences in accuracy between the two. Participants classified the HMD system as an "inside-out" display (looking outwards from inside the volume), and the fish tank and haptic systems as "outside-in" displays (looking inwards from outside the volume). Including haptics added an inside-out capability to the fish tank system through the use of touch. We recommend an outside-in system because it offers both overview and context, two visual properties that are important for the volume visualization tasks we studied. In addition, based on the haptic group's opinion (80% positive) that haptic feedback aided comprehension, we recommend supplementing the outside-in visual display with inside-out haptics when possible.

CR Categories: H.1.2 [Models and Principles]: User/Machine Systems—human factors, human information processing; H.5.2 [Information Interfaces and Presentation]: User Interfaces—evaluation/methodology; haptic I/O; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—virtual reality

Keywords: fish tank, force feedback, haptics, head mounted display, virtual reality, visualization, volume rendering

1 Introduction

Fred Brooks defines a VR experience as "any in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint" [F.P. Brooks 1999]. Although it is difficult to categorize all VR systems, this paper separates them based on their display technology:

- Projection-based VR systems (e.g., CAVE [Cruz-Neira et al. 1993] or workbench [Kreuger et al. 1995]).
- HMD based immersive VR systems [Sutherland 1968].
- Monitor-based desktop VR systems, (e.g., fish tank VR [Ware et al. 1993]).

Visualization researchers increasingly use VR interfaces to build applications for domain scientists to display scientific data in 3D using a variety of visualization techniques [Hansen and Johnson

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*w.qi@tue.nl

2004]. However, there are currently few guidelines regarding which type of display system should be used, especially based on evidence derived from qualitative and quantitative analysis. This can lead to the development of applications whose design may not use the most effective system to solve the domain scientist's problem.

2 Scientific problem

Our collaborators are studying the structure of human lung mucus in both normal "wild-type" lungs and in the lungs of CF patients. This mucus is made up of a number of long polysaccharide molecules called mucins. It is known that there are a number of different types of mucin present in the mucus, and that the mucus is denser for CF patients than wild-type mucus. What is not known is how the different types of mucin are distributed in the mucus, and how particles can diffuse through it.

The mucins may be uniformly distributed, or form distinct domains. There may be web-like superstructures formed by a subset of the mucins which contain clumps of other mucins. There may be large, small, or a variety of differently sized water pockets surrounded by thin membranes. There may be a continuous water path with thin webs of mucins forming a lattice. Our collaborators are probing this by developing fluorescent dyes that attach specifically to each different mucin type; they will scan the mucus with a confocal microscope to produce multiple 3D scalar fields, one for each dye. We wish to display the resulting scalar fields in 3D to help them estimate sizes, distributions, and shapes of any resulting voids and structural elements.

A virus, bacteria, or bacterial colony would traverse the mucus differently depending on its structure. The motion of such pathogens is of great interest to the study of CF, because lung infections are the cause of many CF deaths. Our collaborators are probing this by placing small beads of various radii into the mucus and tracking the Brownian-driven motion of these beads over time to understand how they move through the mucus matrix. We wish to display the resulting motion paths in the presence of the above mesh structure to help our users correlate structure and density with bead motion paths.

With these problems in mind, the data sets and questions of this user study have been designed to help determine which display and interaction system best supports the types of queries our collaborators and users are asking without requiring our participants to be experts in CF. Our collaborators are investigating a number of tasks within a dense volumetric scalar field (for example, connectivity and relative density are of interest in addition to counting, shape, and size analysis). We tried to provide tasks that were similar to our collaborators needs yet as generic as possible, so that the results of the user study could apply to other applications that explore dense 3D scalar fields looking for structure and pathways. We think that oil-field study and tumor segmentation might have similar needs for understanding complex dense data and for studying connectivity between portions of the data (oil reservoirs and blood vessels).

3 Related work

There has been a great deal of effort in the VR research community aimed at developing and integrating new devices and technology to improve the usability of VR systems. Much work has investigated the usability and effectiveness of a VR system at simulating real-world scenarios. Our user study attempts to validate the usefulness of particular VR systems for volume visualization tasks.

The case for stereo in scientific visualization is clear: Ware has shown that stereo combined with motion enables improved user performance in the 3D visualization of graphs, which argues for using VR rather than a traditional desktop display [Ware and Franck 1996]. Arthur's study demonstrated the advantages of a fish tank VR system for 3D tasks compared to desktop displays [Arthur et al. 1993]. Of interest to us is which type of stereo VR system is most effective for scientific visualization of dense volume scalar fields.

The Effective Virtual Environments (EVE) group at UNC Chapel Hill has conducted presence, locomotion and redirected walking studies within immersive HMD VR systems [Meehan et al. 2002; Razzaque and Whitton 2001]. Immersive versus fish tank VR for searching and labeling has been studied by Cagatay [Demiralp et al. 2003], who compared fish tank VR and CAVE displays for a visual search task. The results of their qualitative study showed that users preferred a fish tank display to the CAVE system for a scientific visualization application because of a perceived higher resolution, brightness, crispness and comfort of use. The results showed users perform an abstract visual search task significantly faster and more accurately in a fish tank environment, compared to the CAVE.

Navigation in HMD versus CAVE has been studied by Bowman [Bowman et al. 2002]. He presented a preliminary experiment comparing human behavior and performance between a HMD and a four-sided spatially immersive display (SID). In particular, he studied users' preferences for real versus virtual turns in the virtual environment. The results indicated that participants have a significant preference for real turns in the HMD and for virtual turns in the SID. The experiment also found that females were more likely to choose real turns than males. This suggests that HMDs are an appropriate choice when users perform frequent turns and require spatial orientation.

Schulze [Schulze et al. 2005] presented a user study comparing performance across multiple immersive environments for a counting task. He tested three VR displays: a CAVE-like environment, a single-wall display, and a desktop system (fish tank VR). Data he collected led to four significant findings: (1) in the CAVE the participants preferred medium sized or large spheres over small spheres; (2) when only a few targets have to be marked, larger spheres were marked faster than smaller spheres; (3) large spheres are marked most accurately; and (4) performance for the wall display was not comparable to the fish tank VR display when the spheres were small. Additionally, occlusion and a larger field of view inhibited performance in the CAVE more than in the fish tank display when the task was dominated by visual search.

The scientific visualization community is continually developing better algorithms to represent data in a form suitable for comprehension. Traditional visualization schemes are entirely visually dependent. More and more VR systems for visualization applications incorporate haptic feedback. An early example of haptic representation of scientific data is found in the work of Brooks [Brooks et al. 1990]. Users are assisted by a force reflective master manipulator during a complex molecular docking task. In this work, a force display is used to drive the system towards a local minimum and indicate tightness of fit. The nanoManipulator (nM) [Taylor et al. 1997] is a VR system that provides an improved, natural interface to scanning probe microscopy, including scanning tunneling microscopes and atomic force microscopes. The nM couples the microscope to a haptic VR interface that gives the scientist virtual telepresence on the surface, scaled by a factor of up to a million to one. The Visual Haptic Workbench [Brederson et al. 2000] is another testbed system for conducting research on the synergistic benefits of haptic displays using an integrated, semi-immersive virtual environment.

Several studies have shown the effects of a haptic display on human perception. Studies from Ernst have shown a clear influence of haptics on vision, demonstrating that vision does not necessarily completely capture haptics [Ernst and Banks 2002]. The human central nervous system seems to combine visual and haptic information in a fashion that is similar to a maximum-likelihood integrator. Visual dominance occurs only when the variance associated with visual estimation is lower than that associated with haptic estimation. Our study quantitatively investigates differences in user performance due to the presence or absence of haptic feedback for a visualization task.

Kosara [Kosara et al. 2003] suggested that user studies should be designed to evaluate visualization methods. This also applies to VR systems with visualization capabilities. Previous user studies have offered insight into the appropriate selection of VR systems for universal interaction and manipulation tasks such as rotation, navigation and sparse visual search. Our study extends this work to include several tasks specific to the visualization of dense volumetric data sets.

4 User study

Our user study compares three kinds of VR systems: HMD based VR, fish tank VR and fish tank VR with haptic feedback. The relative performance of these systems is compared over four generic tasks involving the visualization of volumetric data. The rendering paradigms are only tested in their most common configurations: inside-out for HMD and outside-in for fish tank.

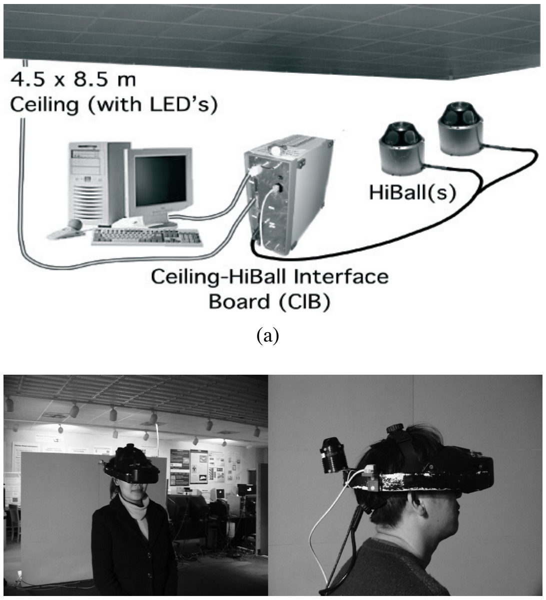
4.1 Apparatus

All three systems display the volumetric data using the Visualization Toolkit (VTK), an open-source library that provides several different rendering algorithms (ray-casting, isosurface and 2D texture mapping). To enable real-time interaction, we chose Marching Cubes as the primary algorithm and render isosurfaces of the volumetric data. The standard structure of VTK does not provide a mechanism for integration with our VR input devices, so we combined the VTK library with VRPN (Virtual Reality Peripheral Network [Taylor et al. 2001]) and UNC's Vlib virtual-world library toolkit to enable access to the visualization capabilities of VTK from our VR setups.

4.1.1 Immersive HMD VR system

Our immersive VR system uses a V8 HMD from Virtual Research System. Each LCD provides a color VGA pixel resolution of 640 × 480 at a refresh rate 60Hz. Head tracking is performed via a 3rdTech HiBall tracking system, a high-performance wide-area optical tracker that incorporates a six degree-of-freedom (DOF) sensor. The HMD/head tracking system consists of three main components as shown in Figure 2a. The outward-looking HiBall sensor is mounted on the back of the HMD (Figure 2b). The HiBall observes a subset of fixed-location infrared LEDs embedded in the ceiling. A tracking server coordinates communication and synchronization between the host computer and the HiBall and ceiling LEDs. Tracking data are transmitted through network switched Ethernet from the tracking server to a rendering computer via VRPN. We used a Dell Precision 530 (dual 2.8-GHz Xeon with 2GB RDRAM) and an NVidia Quadro FX 1000 graphics card. The two VGA outputs from the graphics card are connected to the LCDs for each eye in the HMD via a video splitter to provide stereo-offset images.

The working space for a user in this VR system is about 4.5 meters wide by 7 meters long by 4 meters tall (15 feet × 23 feet × 13 feet). A calibration procedure is used to calculate a precise transformation matrix between the sensor and the eyes. An additional hand sensor is also available for hand input, but it was not used during our experiments.



(a)

(b)

Figure 2: Head-mounted display system: (a) HiBall tracking system; (b) head-mounted display with head sensor

4.1.2 Fish tank VR

The second VR system is based on the concept fish tank VR introduced by Colin Ware. The central computing platform of this VR system identical to the HMD system with the following additional components:

- A 17-inch CRT monitor with resolution of 1024 × 768 and a refresh rate of 100 Hz to support stereo display, an infrared emitter and shutter stereo glasses from StereoGraphics.
- A PHANTOM Desktop$^{\text{TM}}$ haptic device for precise 6-DOF positioning and high fidelity 3-DOF force feedback output at 1 kHz. In fish tank VR mode, the PHANTOM was used to rotate the volume around to its center (additional operations were available during fish tank VR with haptics, as described below).
- A DynaSight 3D optical tracker for measuring the 3D position of a target (reflective disc) attached to the front of the stereo glasses. When dynamic perspective is combined with stereoscopic viewing, a real-time 3D display appears that provides a virtual window into the computer-generated environment. Dynamic perspective eliminates the perceived image warping associated with static stereoscopic displays. An additional benefit of using the head to tune the perspective is that the hands are free to control the object being visualized, in our case with the PHANTOM.

The hardware components are organized to enable accurate and easy calibration. The tracker's control box is placed above the monitor on a metal plate supported by an arm (Figure 3). The arm's height guarantees continuous detection of the tracking and stereo signals. A cable between the infrared emitter for the stereo glasses and the control box for the head tracker synchronizes the devices.

4.1.3 Fish tank with haptics

Haptic visualization techniques have been developed for force feedback systems such as the PHANTOM. The fish tank VR with hap-

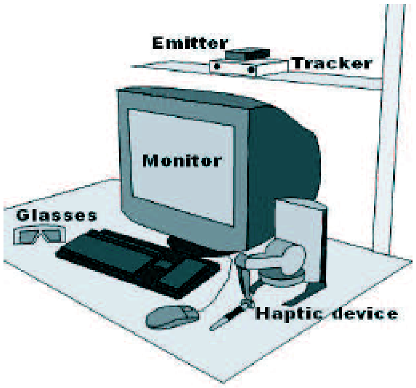


Figure 3: A diagram of the fish tank VR system

tics prototype uses the same hardware setup as the fish tank VR system, except that the PHANTOM also provides force feedback, specifically a single point of haptic response, which is sufficient for our tasks. Although the pen tip where force is applied is not visually located within the display volume (as compared to the Visual Haptic Workbench or the *ReachIn* systems), no users complained about the cognitive effort required to move the hand in one location while viewing another. An axis-aligned on-screen icon followed the pen's motion in 3D, producing an effort similar to using a mouse to control the on-screen cursor. The haptic presentation of volumetric data employed different force models for different objects within the volume: viewers felt the outside surface of spheres and ellipsoids, but the inside of long curved tubes.

4.2 Data and task

Simulated volumetric data are generated to act as trials during our studies. A random number of two to four types of differently-shaped objects (sphere, ellipsoid, cylinder, and curved tube) are inserted with random positions. These objects may overlap with each other. The objects' properties (size, shape, and density) form experimental conditions that vary between trials. The bounding box of the volume is uniformly subdivided into eight subregions (a $2 \times 2 \times 2$ array in the x, y, and z directions) within which object density may differ. Subregions are labeled with unique numbers (1 through 8) to enable participants to describe the paths of curved tubes within a volume.

There are always spheres and at least one curved tube within every volume. Trials may also contain ellipsoids, cylinders, and up to two additional curved tubes. Spheres size may vary over four possible radii ranging from six to twelve units. The density of objects within each subregion is controlled to be sparse, medium, or dense. A single dense region (the "densest"region) exists within each volume. Sparse regions contain between 10%–60% of the number of objects in the dense region, while medium regions contain between 60%–90% of this number.

Participants are asked to complete fours tasks within each trial. Each task involves judging the properties of a specific object or of the overall volume, specifically:

- *Shape task:* Participants identify the number of differently-shaped objects within the volume and name the shapes.
- *Size task:* Participants report how many different sizes of spheres exist.
- *Density task:* Participants identify the densest subregion in the volume.

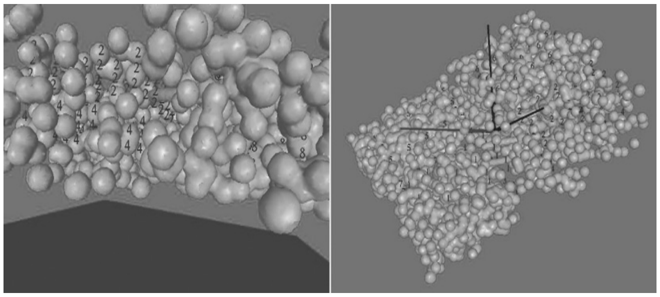


Figure 4: Two views of volume data from an example experiment trial, as seen in the HMD system on the left, and as seen in the fish tank and fish tank with haptics systems on the right

- *Connectivity task:* Participants report how many curved tubes exist in the volume, and then determine which subregion(s) the longest curved tube passes through. For example, Figure 1 shows two curved tubes.

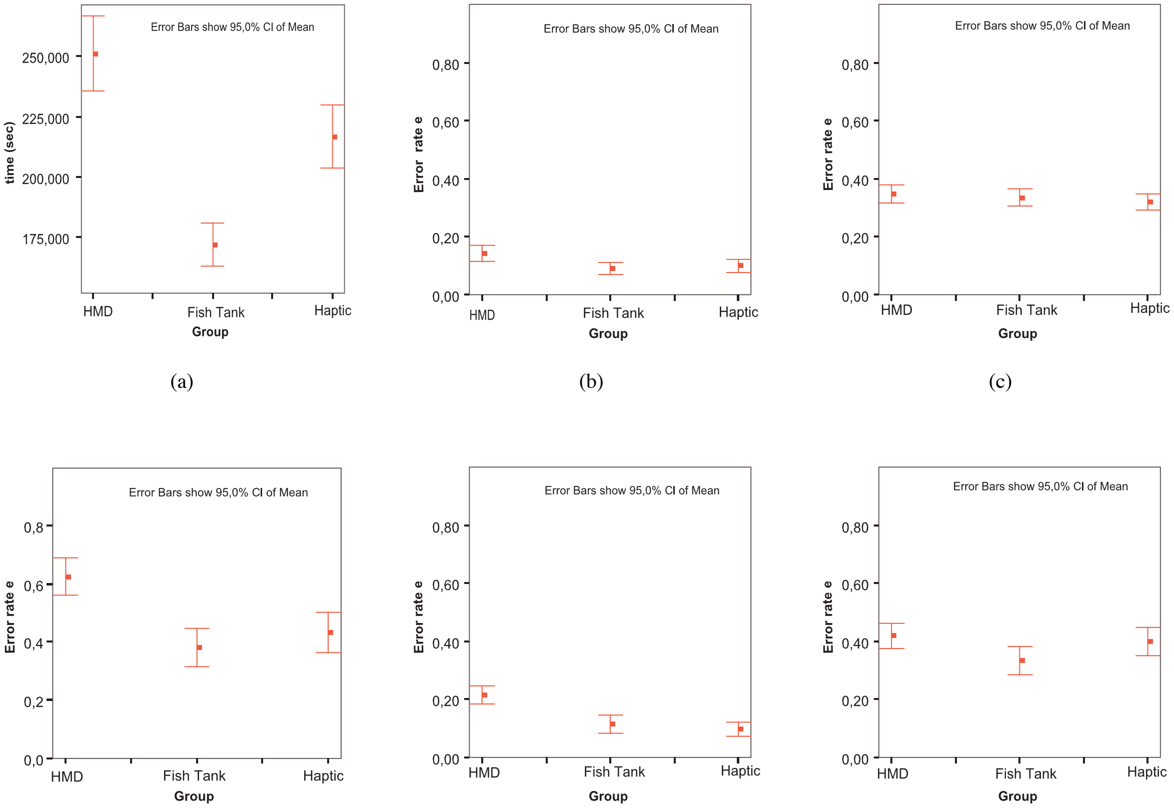
Participants are asked to answer as accurately as possible and to minimize response time. The size, density, and curve counting questions are presented in a multiple choice format. Participants are asked to describe the name of each kind of object for the shape question and all the sub-region numbers for tube tracking question.

4.3 Experimental procedure

A between-subjects design was used, with VR system type as an independent factor: HMD, fish tank VR, and fish tank VR with haptics. Participants were randomly assigned into one of three groups. The HMD group wore the HMD and walked around within the tracked environment to observe the volumetric data. The fish tank group used the fish tank VR system and wore stereo shutter glasses to interact with volumetric data through the stylus of the PHANTOM. Although the stylus was tracked and displayed as an icon on the monitor, no force feedback was provided to this group. The haptics group added force feedback to the basic fish tank VR system.

Participants completed several steps during the experiment. As part of an initial interview session, they signed a consent form, answered basic demographic questions (age, gender, and occupation or major field of study), and identified their frequency of computer use and prior experience with any kind of VR system. A training session introduced the equipment and described the tasks to be performed. Next, the formal experiment session was conducted. Each experiment included 20 trials, with each trial containing a single volumetric data set. These twenty data sets were completely different from one another, and vary by object property (type, size, position, and density). However, the same set of trials (20 data sets) in the same order were used for all three groups (HMD, fish tank, and fish tank with haptics).

Two dependent variables, the time taken to respond for each trial and the participant's accuracy for each task, were recorded. For the density question and the question about which subregions does the longest tube passed through, accuracy was recorded as 1 for correct and 0 for incorrect. For other questions, accuracy is the percentage of correct answers. A short break was provided every half hour or whenever a participant asked for one. After completing the last trial in the formal experiment session, participants filled out a questionnaire describing their preferences about the system, any suggestions they had on how to improve the system, and so on. The study ended with a short debriefing during which the experimenter



(a) (b) (c)

(d) (e) (f)

Figure 5: Mean *rt* and *e* values for the different experiment conditions, all results are divided by display system (HMD, fish tank, fish tank with haptics), error bars represent 95% confidence interval: (a) mean *rt*; (b) mean *e* for the shape task; (c) mean *e* for the size task; (d) mean *e* for the density task; (e) mean *e* for counting during the connectivity task; (f) mean *e* for spatial region tracking during the connectivity task

summarized the study goals. The participants were paid $9 for their participation.

5 Results

Forty participants volunteered for our experiment, thirty three males and seven females. The participants were randomly assigned into one of the three display system groups: 14 participants (12 males and 2 females) for the HMD group, 13 participants (11 males and 2 females) for the fish tank group, and 13 participants (10 males and 3 females) for the haptic group.

The age of each participant and the frequency of computer use (on a scale from one to seven) were recorded before the experiment began. Average ages and frequencies of computer use were 23.2, 23, and 23.7, and 6.3, 6.0, and 5.6 for the HMD, fish tank and haptic groups, respectively. These data suggest we had similar ages and computer experience within each group.

5.1 Summary

Two measures of performance were compared for each trial a participant completed: response time *rt* and error rate *e* (where error rate is one minus accuracy). A single *rt* value representing the total time in seconds needed to complete all four tasks was captured for each trial. Four separate *e* values for the four tasks the participant completed were generated.

For *rt* statistics, trials were divided by display system (HMD, fish tank, or fish tank with haptics). For *e* statistics, trials were divided by display system (HMD, fish tank, or fish tank with haptics) and task (shape, size, density, or connectivity). Average *rt* and *e* for different conditions were then compared using analysis of variance (ANOVA). In summary, the following significant differences in performance were identified:

1. The HMD group had longer *rt*, compared to both the fish tank and the haptic groups. In addition, the haptics group had longer *rt* than fish tank alone.
2. For the shape, density and connectivity tasks, the HMD group had higher *e*, compared to both the fish tank and haptics groups.
3. In counting number of different sizes, the HMD group had higher *e* than the fish tank and the haptics groups when only one size was present. When more than one size was present, participants in all three groups tended to underestimated the number of sizes.

5.2 Analysis of results

The response time *rt* needed to complete all four tasks during each trial was recorded during the formal experiment session. Participants in the HMD group had significantly higher *rt* compared to the fish tank and haptic groups, $F(2,615) = 37.16, p < 0.001$, $rt = 251\,\text{s}, 172\,\text{s}$, and $216\,\text{s}$ for the HMD, fish tank, and haptic groups, respectively (Figure 5a). The ANOVA for the logarithm of *rt* was also significant, $F(2,615) = 40.058, p < 0.001$. Post-hoc paired comparisons showed that the fish tank group was significantly faster than the haptic group ($p < 0.001$). Because of the high *rt* for the HMD group (which seemed to be caused by fatigue due to wearing the HMD), we were forced to reduce the total number of trials for this system to 16. Because each trial tests all four tasks, this did not unbalance the experiment to favor certain conditions. Although participants in the other two groups were able to finish all 20 trials within the allotted time, to maintain consistency we analyzed only the first 16 trials completed in each group.

For the shape task, e for the HMD group was significantly higher than the fish tank and haptic groups, $F(2,637) = 5.186, p = 0.006$, with $e = 0.14, 0.09$, and 0.10 for the HMD, fish tank, and haptic groups, respectively (Figure 5b). Post-hoc paired comparisons showed no significant difference between the fish tank and haptic groups during this task.

For the size task, there was no significant difference in accuracy, $F(2,637) = 0.874, p = 0.418$. In absolute terms none of the groups was highly accurate. Error rates were all above 30%, although fewer errors were made during the haptic trials, with $e = 0.35, 0.34$, and 0.32 for the HMD, fish tank, and haptic groups, respectively (Figure 5c).

In the density task, e for the HMD group was again significantly higher than for the fish tank and haptic groups, $F(2,637) = 15.153, p < 0.001$. Post-hoc paired comparisons showed no significant difference between the fish tank and haptic groups. In absolute terms, none of the three groups had high accuracy, $e = 0.63, 0.38$, and 0.44 for the HMD, fish tank, and haptic groups, respectively (Figure 5d).

In the connectivity task, participants answered two questions: the total number of curved tubes in the volume, and which subregions of the volume the longest tube passed through. For the numerosity question, the HMD group had significantly higher error rates than the fish tank and haptic groups, $F(2,637) = 20.118, p < 0.001$. Post-hoc comparisons showed no significant differences between the fish tank and haptic groups. In absolute terms, the haptic group was somewhat more accurate than the fish tank group, $e = 0.22, 0.11$, and 0.10 for the HMD, fish tank, and haptic groups, respectively (Figure 5e).

For the spatial region question, the HMD group had a significantly higher e, compared to the fish tank and haptic groups, $F(2,637) = 3.543, p = 0.029$, $e = 0.42, 0.33$, and 0.40 for the HMD, fish tank, and haptic groups, respectively (Figure 5f). Although the haptic group is less accurate than the fish tank group in absolute terms, the difference was not significant.

5.3 Discussion

The time needed to complete tasks in the HMD system was significantly longer than in both the fish tank and the fish tank with haptics systems. One explanation is that the HMD system requires participants to walk around within the tracking space, which takes more time to explore compared to moving hands and head in the fish tank systems. Another critical issue was the reported inability of HMD participants to remember where they had previously seen target items within the volume. They would often have to re-search the volume for objects they had previous located, but had “lost” as they walked into a different region. Finally, participants may simply be more familiar with a standard desktop system.

The fish tank group was also significantly faster than the haptic group. When touch was available, participants often felt inside the volume to confirm their decisions, even when a correct answer could be derived from visual evidence alone.

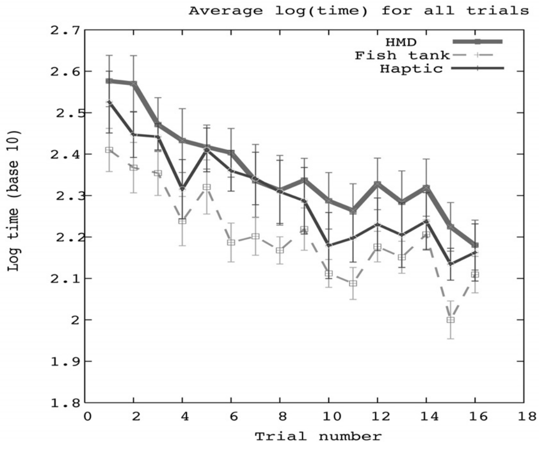


Figure 6: A time curve for each VR system, in the order that participants completed the trials.

A curve of the time spent on each trial indicates a learning effect for all three groups. Time decreased as participants completed more tasks (Figure 6). The first five tasks show the strongest learning tendency. The learning effect did not affect the ability to draw conclusions because the three groups shared the same learning pattern.

The HMD group was significantly less accurate than the fish tank and haptic groups in the shape task. Error results showed that participants from all three groups found it relatively easy to identify the sphere and ellipsoid objects. The HMD group made more mistakes identifying cylinders than the other two groups. Finally, participants from all three groups sometimes misjudged the curved tube as a cylinder.

Although there were no significant differences in accuracy during the size task, absolute performance was poor across all three groups. When there was only one size of sphere, the responses were quite accurate except with HMD ($e = 0.43, 0.15$, and 0.0 for HMD, fish tank, and haptic, respectively). When two sizes of spheres with a large difference in radii were presented, the participants also did well. However, when the radii difference between the two spheres was small, or when there were three or four different sizes of sphere, all participants had difficulty determining how many different sizes were present ($e = 0.76, 0.78$, and 0.86 with three sizes of sphere, and $e = 0.93, 1.0$, and 1.0 with four sizes of sphere for HMD, fish tank, and haptic, respectively). This suggests that: (1) some of the radii differences were too small to be easily distinguished by the visual system; and (2) asking participants to compare between more than two objects (e.g., three or more different sized spheres) may negatively affect their accuracy.

For the density task, the HMD participants were significantly less accurate than the fish tank and haptic participants. None of the three groups had high accuracies, however. There was no significant difference between the fish tank and haptic groups, implying that haptic feedback did not help with finding spatial regions with a different density of objects. The errors for all three groups were spread out across the trials, and showed no learning effects. This suggests that identifying regions of varying density within a 3D volume is a difficult task that none of these three display systems fully supports.

For the connectivity task, participants are asked to count the number of curved tubes in the volume, then locate the longest curved tube and identify which subregions of the volume it passed through. For the counting question, HMD participants were significantly less accurate than fish tank and haptic participants. The ability to feel along the inside of the tubes helped the haptic group provide slightly more accurate counts of the number of unique tubes contained within the volume.

For the connectivity task's spatial region question, the HMD group was significantly less accurate than the fish tank and haptic groups. The fish tank group was slightly but not significantly more accurate than the haptic group. Task analysis for this question shows that participants first had to identify which tube is longest by comparing the lengths of all the tubes, then to determine which subregions contain the target tube. If the wrong tube is identified as longest, the final answer will also be wrong.

In the HMD system, participants often judged the wrong tube to be the longest one. For the fish tank and haptic systems, when the length differences among the tubes were large, haptic feedback helped participants locate the longest tube by touch. They could then correctly identify the subregions containing the tube. When the length differences were small, visual feedback acted as the main determinant in locating the longest tube. This explains the slightly different error rates between the fish tank and haptic systems. Our results match the findings of Ernst and Banks [Ernst and Banks 2002]: when visual and haptic feedback are present and haptic feedback can add a definite assistance for a task or judgment, it will be used. Otherwise, visual feedback is still the dominant sensory input.

In addition to statistical results, a number of interesting anecdotal findings were made, pointing to: (1) the desire for an overview display in the HMD system; (2) the desire for immersion in the fish tank VR systems; (3) fatigue in the HMD system; and (4) the preference for including touch in the haptic system.

Several HMD users spontaneously suggested adding the ability to see a high-level overview (which might be provided through a button press, Mine's head-butt zoom, or a worlds-in-miniature interface). One casual user was tall enough that he stood above the data, enabling him to get an overview in the HMD system, which he reported to be useful. This matches our later analysis as well as issues related to the effects of memory on participants' results.

Some participants in the fish tank and haptic groups wanted to zoom in and see the volume from the inside (some tried to do this by moving their head near the screen). We concluded that both overview and immersion are helpful for performing our tasks. Anecdotal and formal results indicate that a system designed for the study of dense volumes should include both capabilities.

Most participants said that the HMD and haptic systems were "cool" or "neat" upon initial exposure. Several participants mentioned without being asked that they liked the HMD VR system. However, participants in the HMD group requested more breaks and sometimes asked "How many trials do I still have?", indicating dissatisfaction with the system. We believe this is due to physical or mental fatigue. The increased number of breaks requested did not happen in the fish tank or the haptic cases.

5.4 Subjective results

Subjective measurements were obtained through analysis of the post-experiment questionnaires. Most of questions used a standard seven point rating scale. The answers indicated that overall, participants preferred the haptic and HMD VR systems due to perceived ease of use, presence, and immersion. We summarize our findings over the following categories of questions we asked.

Perception of a VR system. The first category asked about the perceptual properties and characteristics of a VR system, including the immersion, presence, depth, and spatial relationships. For the question: "the extent you felt you were within a virtual environment" the HMD system ranked significantly higher than the other two systems, $F(2,37) = 5.481, p = 0.008$, with a post-hoc comparison between HMD and haptic of $p = 0.006$, and absolute rankings of 6.0, 5.4, and 4.4 for HMD, fish tank, and haptic, respectively. There was also a significant difference on the question: "the extent you have a sense of acting in the virtual space, rather than operating something from outside." The HMD system ranked significantly higher than the other two systems, $F(2,37) = 15.666, p = 0.001$, with scores of 5.9, 3.1, and 4.4 for HMD, fish tank, and haptic, respectively. Further post-hoc comparison showed the fish tank with haptic system ranked significantly higher than fish tank alone due the existence of touch ($p = 0.03$), indicating that haptic feedback does add an inside-out property to a fish tank display. For the question: "the extent you feel that the virtual environment surrounded you" the HMD group again ranked higher than the other two groups, $F(2,37) = 16.464, p = 0.001$, with scores of 6.3, 3.0, and 3.2 for HMD, fish tank, and haptics, respectively. This suggests that HMD participants felt more strongly that they were acting within a virtual environment. We found no notable differences on the questions: "a sense of being there," "a sense of immersion," "difficulty of understanding the spatial relationships" "the quality of multiple view points," or "the quality of depth cues," although the HMD system did rank slightly higher in absolute terms in the immersion, presence, multiple viewpoints and depth cues questions.

Usability of a VR system. The ease of learning and using a VR system is the main focus of this category. Answers to the question: "how much consistency do you experience in VR compared with a real world experience" were similar for participants from each group. There were no obvious differences on the question about system delay, although HMD participants reported a slightly shorter perceived delay. The haptic system ranked higher than the other two systems for identifying the shape and location of individual objects, and the shape of the global topology. Although participants from all three groups felt their system was easy to use, the HMD group ranked highest for the perceived difficulty in carrying out their tasks. Moreover, HMD participants reported a significantly higher demand for memorizing than the other two groups, $F(2,37) = 5.534, p = 0.008$, with scores of 5.2, 3.6, and 3.7 for HMD, fish tank, and haptics, respectively. Finally, HMD participants were less confident about the accuracy of their answers, $F(2,37) = 5.521, p = 0.008$, with scores of 4.1, 5.2, and 5.2 for HMD, fish tank, and haptic, respectively. No participant from any group complained about the resolution, frame rate or delay; these parameters did not seem to bother them.

The added value of haptics. The use of haptics enables participants to employ multiple sensory modalities to perform tasks. Most participants in the haptic group were excited about the additional functionality, and claimed that haptic feedback did help in some way. 80% of the participants from the haptic group thought the visual and haptic information was consistent, and that searching the virtual environment through touch was easy. 75% of the participants thought touch helped them better understand the space, and 80% thought it helped understand global structure. Participants reported that haptics was especially helpful for the connectivity questions: "How many curved tube are there?" and "Please name all the subregions the longest tube crosses." because the tubes are hidden behind other objects.

6 Conclusion

This paper presents results of an empirical evaluation comparing performance using different VR systems for four generic volume visualization tasks. The tasks were derived from particular data set characteristics and questions being asked by our collaborators studying mucuciliary clearance in CF. Results showed that a haptic system offers participants both an inside-out and an outside-in perspective on a volume, a property that was identified as important for completing our tasks. Participants using the HMD VR system were significantly slower than participants from the other two systems, and were less accurate for the shape, density, counting, and spatial tracking questions. Finally, none of the systems enabled accurate judgment of different sizes of objects, or of which regions of a volume had the densest spatial packing.

The speed difference for the HMD system was not unexpected, but the inferior task performance was quite surprising. Participants' responses to questionnaires and anecdotal comments reveal that memory load was a significant factor. In the absence of an overview capability, participants were forced to make an internal representation of the total volume; the dense nature of the data removed visible landmarks that can normally provide such a frame of reference. We are considering a future system that includes both an overview and an inside-out capability within the HMD. This system will be studied to determine if its performance is at or above the level of the haptic-enabled system for some tasks.

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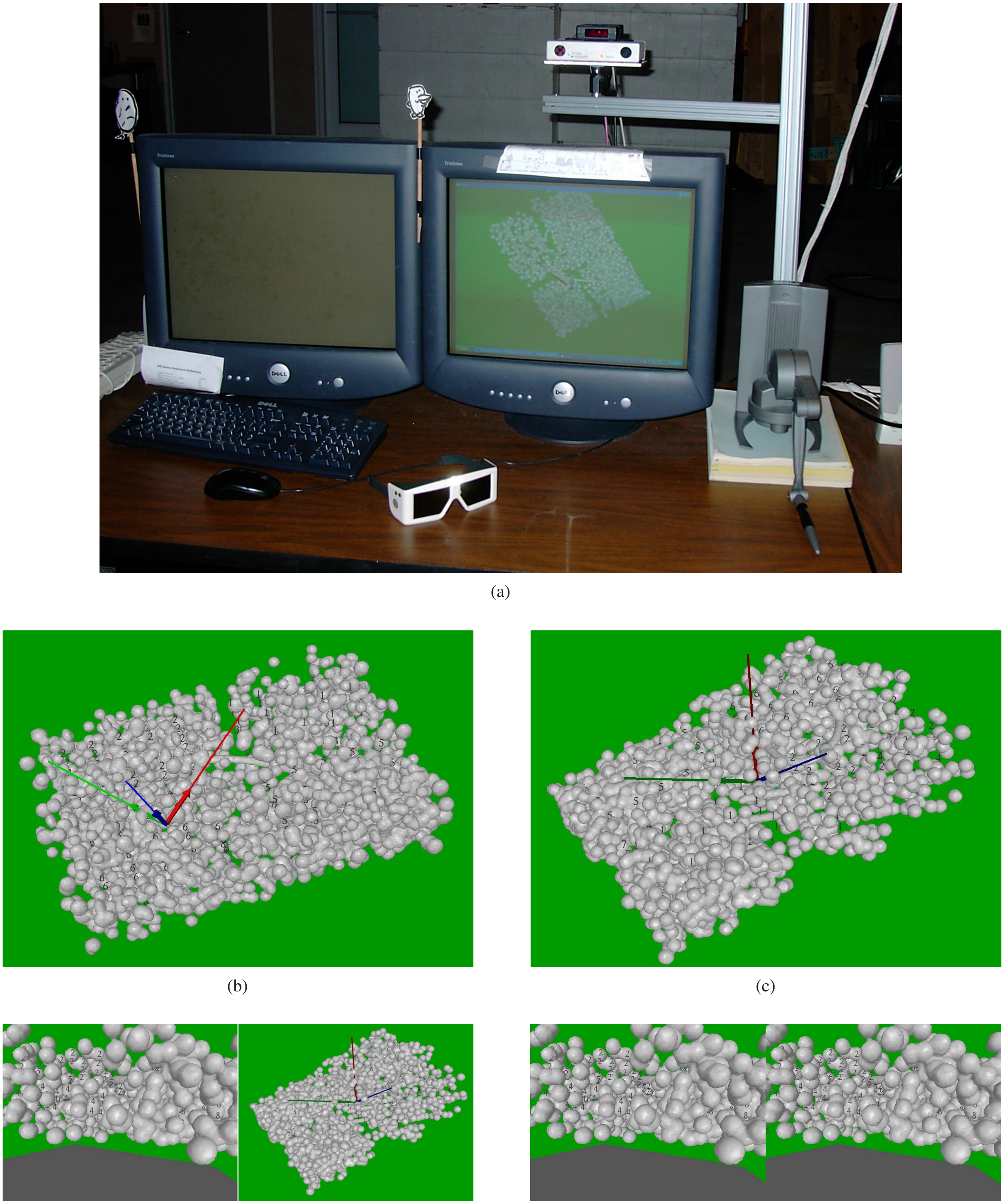

(a)

(b)

(c)

(d)

(e)

Figure 7: Examples of the experiment setup and displays: (a) the fish tank display with StereoGraphics shutter glasses, a head tracking unit, and a PHANTOM haptic device; (b,c) two examples of volumes viewed in the fish tank environment; (d) a volume viewed in the HMD environment (left) and fish tank environment (right); (e) left and right eyes of a volume viewed in the HMD environment