Part IV
Novel User Interfaces

Chapter 10
Virtual Reality-Based Interactive Scientific Visualization Environments

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Abstract Immersive Virtual Reality (IVR) has some production applications (e.g., in vehicle design and psychiatric treatment), but it is often viewed as an expensive, over-hyped technology with insufficient and/or unproven benefit over conventional desktop systems. With steady research progress at many institutions and advances in hardware and software technologies, immersive scientific visualization is a third application area in which IVR is having a positive impact and is beginning to attract more attention from the scientific community. At Brown University, we have been researching immersive scientific visualization systems by developing interactive systems with domain scientists in a variety of fields, including archaeology, biology, computational fluid dynamics (CFD), and geoscience. Anecdotal and formal evaluations show the benefits range from mild to very significant – benefits include speeding up and providing broader analysis, greater spatial understanding, enabling new types of exploration, helping in undergraduate as well as graduate courses, and debugging data acquisition methods. In this chapter, we present a number of these systems developed at Brown University and discuss the results of our experimental findings on the efficacy of IVR-based interactive visualization.

Keywords Immersive virtual reality, Scientific visualization, Interactive visualization, 3D interfaces, Surround screen display, Virtual environments.

10.1 Introduction

Scientists studying the physical world frequently need to analyze complex data sets (multidimensional, multivariate, time-varying) and models. Our group of interactive visualization researchers subscribes to the theory that in order to best understand such data we must "impedance match" display and interaction devices as best we can with human motor and sensory capabilities, in a task-dependent way. We feel

that for 3- or higher-dimensional data this is best done by immersive virtual reality (IVR) systems, with their ability to provide greatly enhanced 3D depth-perception via head-tracked stereo. There is also mounting evidence that IVR's ability to let users be "inside" their data or model and to interact directly with the data by moving their heads, bodies and hands (body-centric interaction) speeds up the processes of perception and interpretation. Scientific visualization and IVR are both technologies that have a history of invention and development spanning over multiple decades. Indeed, the use of IVR for scientific and information visualization dates back to the early uses of virtual reality [7]. In multiple articles [14, 15, 28, 29, 34, 40, 48], examples have been presented of applications combining these two technologies, as well as evidence for their effectiveness ranging from anecdotal or observational to controlled quantitative user studies. There have also been important studies [8, 26, 34, 35] trying to document how one measures the degree and effectiveness of the dominant psychophysical experiences of presence and immersion provided by IVR; roughly these two experiences relate respectively to the feeling "of being there" and the feeling of being surrounded by a model or data set.

Among the reasons for the potential effectiveness of immersive environments for scientific visualization are (1) the ability to use body-centric interaction, e.g., moving one's head and/or body to gain a different point of view, and using one's hands, potentially aided by voice, to interact with the data or model. Such interactions can be more fluid and more efficient, i.e., with reduced cognitive load, than those controlled by the standard desktop display's keyboard and mouse-driven graphical user interface. (2) the ability to move quickly between large-context views and more detailed views and to have 3D depth-perception significantly enhanced by stereo and low-latency head movement (motion parallax). Being able to hold a model or data set in a fixed position and moving one's point of view, whether on the outside or inside, is far more natural and efficient than holding one's viewpoint fixed and moving the data set. However, head/body movement is not sufficient by itself and a variety of techniques exist [3] for examining new locales within one data set or model using physical interaction devices such as a 3D mouse or tracked glove. (3) the ability to have not only fully immersive environments such as those produced by a head mounted display (HMDs) or CAVE™ [10] but also semi-immersive environments (e.g., Fishtank VR [43] on the desktop or tiled-display walls [41] that still allow head-tracking and use of one's peripheral vision.

At Brown University, we have been developing IVR-based interactive visualization systems and studying their effectiveness for the last 15 years using our Cave, a variant of the CAVE™ and Fishtank VR. In this chapter, we highlight a number of these systems and discuss some of our experimental findings on the efficacy of IVR-based interactive scientific visualization. Readers should note that many other academic institutions and organizations have worked on multiple aspects of Virtual Reality for a number of years. We cannot possibly do justice to all of our colleagues within the space constraints of a single chapter. Indeed that would be an entire book in its own right! If readers are interested, they may refer to the following sampling of literature as a good starting point: [2, 5, 9, 10, 12, 16, 17, 24]; Mine et al. 1997; [Au2] [30, 31, 36, 38, 39, 44].

10.2 IVR-Based Interactive Visualization Systems

Brown University has had a long history in developing interactive scientific visualization systems with carefully designed and evaluated user interfaces from both a visualization and interaction point of view. We believe immersive virtual reality has the potential to provide substantial benefit for these complex visualization problems. In this section, we discuss some of the IVR-based interactive visualization systems we have developed.

10.2.1 Widget Library

In the early 1990s, we began work on 3D user interfaces for desktop and immersive scientific visualization applications working with NASA Ames Research Center over a five year period. The work was inspired by Bryson's Virtual Windtunnel project [6, 7], one of the first systems to explore how scientific visualization could be conducted in IVR. The final user-interface project with NASA led to the development of a stand-alone library for creating and interacting with 3D widgets. The core of the library was a set of building blocks for constructing custom 3D widgets and functions that handle direct manipulation of the widgets (see Fig. 10.1).

In addition to the basic widget building blocks, the library supported interactive shadows and gestural navigation controls (i.e., translation forward and backward, virtual trackball rotation, and film-plane translation) using a single mouse button. These camera controls were derived from the camera controls used in the SKETCH system [46].

In particular, we developed interaction techniques for positioning probes in three-dimensions, controlling both spatial and non-spatial parameters of several visualization techniques, utilizing six-degrees-of-freedom input devices, navigating a 3D virtual world, managing voice annotations, in addition to developing an approach for rapid-prototyping custom input devices.

As an extension to the work done with NASA, we explored how multimodal interfaces could be used in an IVR-based visualization system with the Multimodal Scientific Visualization Tool (MSVT) [22]. MSVT used a rear-projected display device and combined speech input with pinching postures and gestures. The main objective of MSVT (see Fig. 10.2) was not only to build a natural and intuitive interface for a scientific visualization application, but also to explore different multimodal input combination styles [25] such as when two modalities complement each other (e.g., a user asking for a visualization tool with speech while simultaneously pointing to where it should be placed).

10.2.2 Virtual Cardiovascular Laboratory

Towards the late 1990s, we began to focus more on multi-disciplinary collaborations with doctors and scientists to see how IVRs could help them with their visualization
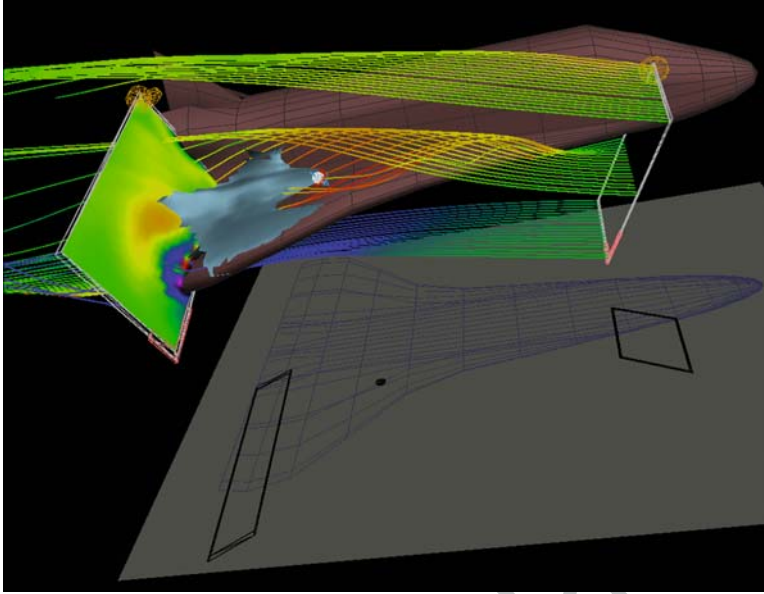
Fig. 10.1 Three example widgets developed as part of the Brown Widget Library developed in the mid-90s under NASA sponsorship to help scientists interactively visualize flow data past a space shuttle model. A color plane of flow speed (far left), an isosurface of flow speed widget (around the bluish-gray surface geometry), and a streamline source widget are shown. Each may have visualization parameters adjusted via direct manipulation of geometry "handles" making up the widget, as well as be transformed (resized, translated, or dragged via interactive shadows)

Fig. 10.2 A user interacting with a dataset for visualizing a flow field around a space shuttle. The user simultaneously manipulates the streamlines with his left hand and the shuttle with his right hand while viewing the data in stereo. The user asked for these tools using speech input

problems. One of the first systems we built along this path was for visualizing coronary artery grafts. These grafts regularly fail for unknown reasons, possibly related to the characteristics of fluid flow around these new arterial bifurcations. When they fail, they require repeated heart surgeries and often cause heart failure. Thus, doctors need tools to better understand cardiovascular hemodynamics.

We built a *Virtual Cardiovascular Laboratory* [14, 37] that coupled numerical simulation of graft geometry with an immersive surround-screen virtual environment for studying the resulting flow data (see Fig. 10.3). To support 3D interaction, we used trackers and pinching postures so users could pull themselves through space to examine artery structure. When users looked down, a virtual toolbelt appeared so they could grab dust for advecting particles through the flow, an "Alka-Seltzer" widget for creating a persistent source of advecting particles, and widgets for choosing wall coloring, streamlines, and rakes.

This system has not yet resulted in novel scientific results partly because we are still learning how to simulate the models of interest. Nevertheless, domain scientists believe the virtual cardiovascular laboratory quickly verified previously discovered results due to the human-sized visualizations (vessel walls and the data within were scaled-up such that they were about eight feet in diameter) that researchers could move inside of and carefully study intricate flow features throughout the volume. Researchers previously studied these kinds of flows in a laboratory setting with life-sized models (vessels on the order of millimeters in diameter with fluids flowing through them) and photographs of dyes injected into the vessel were carefully analyzed to piece together the overall 3D flow behavior.

10.2.3   Archave

Archaeologists base the analysis of data from an excavation site on the physical descriptions recorded in trench reports, site plans, drawings, and photographs. One of
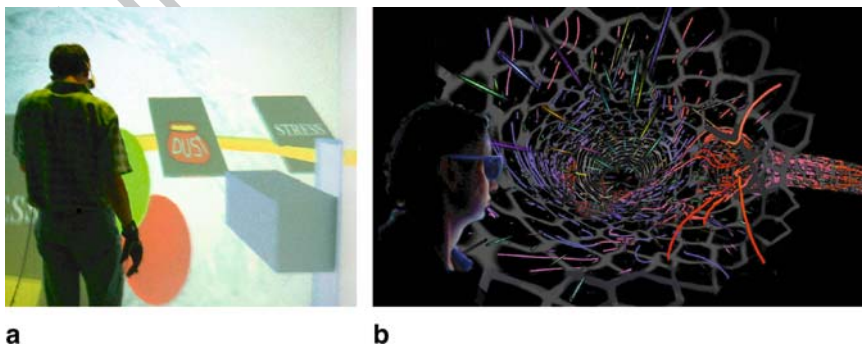

Fig. 10.3   a A user looking at the virtual toolbelt in the Virtual Cardiovascular Laboratory. **b** A visualization of an artery using particle flurries

the main challenges they must face is in understanding the complex spatial relationships existing between the artifacts and the site's architecture. Furthermore, site excavations are a destructive process so accurately capturing and later integrating data reliably is also important. To assist archeologists with their research, we developed the ARCHAVE system, a surround screen IVR application that puts users in a three-dimensional model of *in situ* architectural ruins [1]. Specifically, ARCHAVE was used to visualize the great temple site in Petra, Jordan and the associated trenches and artifacts that have been excavated over the years (see Fig. 10.4).

With ARCHAVE, users navigate in the environment, using a 3D mouse and wear a tracked glove to query the database site information. A standard database of artifact finds has been consistently updated since excavations began in 1993, and it can be queried in real time from the application. Users can also use a miniature version [23] of the full-scale model as a reference to quickly travel anywhere in the virtual environment.

10.2.4   Fluid Mechanics of Bat Locomotion

Building on the work done for ARCHAVE and the Virtual Cardiovascular Laboratory, we began collaborating with researchers from computational fluid dynamics and evolutionary biology to study bat flight fluid dynamics using visualization (see Fig. 10.5). Bats are energy efficient and highly maneuverable, making the study of bat flight likely to yield insights of use in future technological application, such as the development of unmanned flying machines. The mechanisms of their flight are currently not well understood and are challenging to study.

The data field describing airflow around the bat's wings can be described by a combination of many quantities including velocity, vorticity, pressure, and rate of strain. Each of these is a function of both space and time. Additional data describe the intricate motion of the score of bones in each wing, the deformation of the flexible surface of the wing, and interactions between the flow and the surface of

Fig. 10.4   Users exploring the Great Temple Petra with the ARCHAVE system
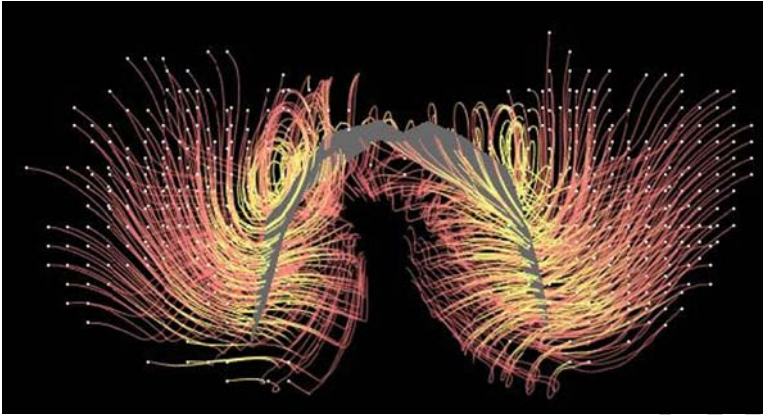
Fig. 10.5 Snapshot from an immersive visualization of bat flight highlighting vortical structure, a signature of lift, near the bat wing surface

the bat. To address the challenge of creating effective tools to visually portray the complex kinematics of the anatomy together with the fluid dynamics, we formed strong collaborations with visual designers at the Rhode Island School of Design (RISD). Visual designers, particularly illustrators, are trained specifically to solve constrained visual problems, and this training can effectively carry over into virtual environment (VE) applications.

With the designers' input, we developed a surround-screen IVR system for visualizing bat flight using several different visualization techniques including particle "eels" that followed pathlines, vorticity-seeded time-varying streamlines for visualizing vortices, and advecting vortex-seeded "snow" to capture wake structures. The user has control over the density of visual elements, how they are distributed in space, and the mapping of color and opacity to flow quantities. These controls allow users to explore a continuum between localized visualization of detected vortices and the contextual flow around them [28].

10.2.5 Diffusion MRI Visualization

In addition to visualizing bat flight and coronary artery grafts, we also developed techniques to visualize diffusion MRI data in IVR, primarily gathered from brain tissues. Diffusion tensor MRI, often abbreviated DTI, is an imaging modality that measures fiber-tract trajectories in fibrous soft tissues such as nerves and muscles. The datasets produced are volumetric, with six interrelated values at each spatial location, and hence are a significant challenge to visualize and understand.

We developed stream tube and stream surface geometric models [48] that relate to the interesting structures in the tissue while representing the DTI data with a

focus on studying white-matter structures to understand changes due to a number of pathologies and for pre-operative planning for tumor surgery. In the VE, geometric models representing the white matter structures and planes showing sections of anatomical scan data generally are kept stationary above a virtual table. The user walks around and adjusts his head position to observe the data from different perspectives (see Fig. 10.6). We generated a yellow line akin to a laser pointer from a 3D mouse in the direction the mouse is pointing. The line stops where it hits an object. The user can use this virtual laser pointer to indicate a region of interest to others, which is particularly useful in the case because different users see different views. The user can also change the position of the slice or cycle through axial, coronal, and sagittal sections with the buttons on the 3D mouse [48].

10.2.6   Adviser

Collaborations with the geological sciences department at Brown has led to the development of the Advanced Visualization in Solar System Exploration and Research system (ADVISER), that lets researchers go "into the field" using our surround screen VE (see Fig. 10.7). Places like Mars and Antarctica are mimicked in ADVISER using satellite data and other computed data like climate models. ADVISER's implementation is a set of tools that provides planetary geoscientists with the capability to operate and analyze data as if they were on or near the surface of a planet. These tools let these scientists go virtually into the field, perform traverse planning for rover missions, take measurements, and conduct global climate model simulations [15].

Users navigate across planetary surfaces using a 3D mouse to point in a particular direction, moving along that vector at a speed proportional to how hard they push on an analog joystick mounted on the device. In addition, they can also bring a Tablet PC into an ADVISER session. The tablet provides them with a 2D view of a planetary surface where they can sketch out paths they want to explore.

Fig. 10.6 Users interacting with the brain dataset in the Brown University Cave
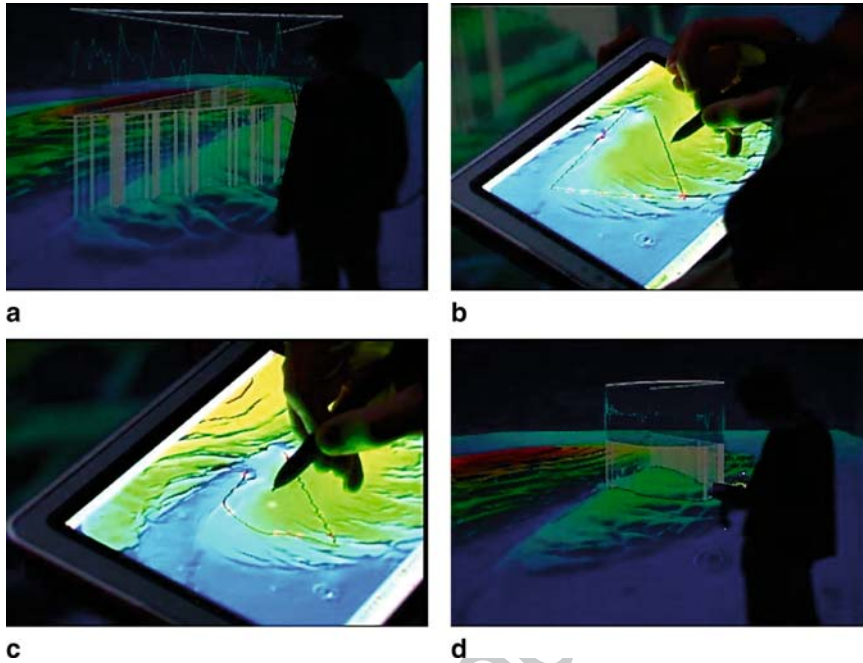
Fig. 10.7 A traverse planning operation in ADVISER. **a** Initial traversal is visualized in the IVR by a line that snaps to the terrain and vertical bars that connect it to a graph of slope (opaque bars indicate slopes too steep for rovers traversal, transparent bars indicate safe slopes), **b** The TabletPC's view of the initial traverse. **c** The user sketches out a new traverse and (d) the system updates the traverse and slope visualization

10.2.7   VOlume eXplorer

Laser scanning confocal microscopy has revolutionized biological science research during the past 10–15 years by providing biologists with the ability to collect high resolution images while eliminating out-of-focus information which is associated with image degradation. Despite the dramatic technological improvements that confocal microscopy and the development of new synthetic fluorescent molecules have brought to the biological sciences, the reconstruction and analysis of a series of optical sections still poses a profound challenge to most researchers. As part of a collaboration with developmental biologists, we designed and implemented Cave VOX, (VOlume eXplorer) a system for studying digitized volumes of multi-channel data from confocal microscopy (see Fig. 10.8).

VOX's user interface uses a set of rectangular widgets on the left wall of our Cave. These widgets are permanently displayed at fixed positions. We chose to display them in the plane of the screen so they are always projected at the same position, independent from where the head-tracked user is looking. Due to the unavoidable
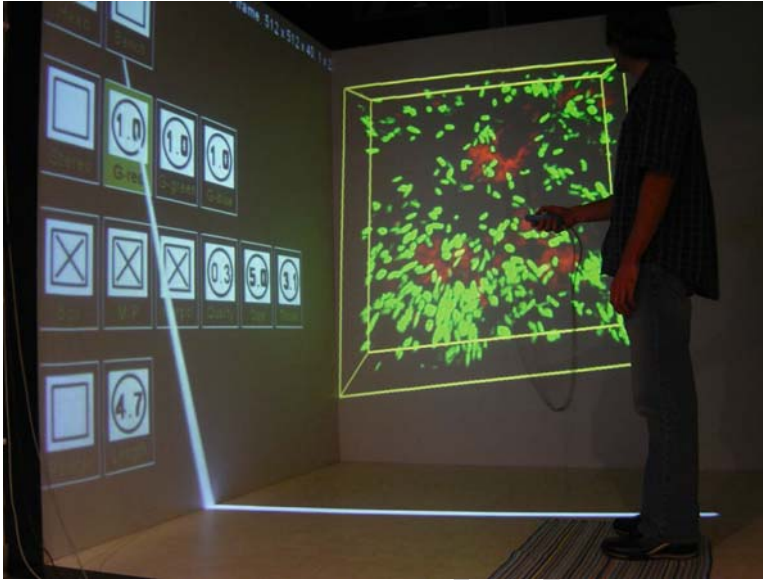
Fig. 10.8 A scientist can adjust visualization settings to tune the 3D visualization on the front wall of the Cave

tracking lag, this gives them a much more stable feel than free-floating widgets, and even for non-tracked users, they are always in the same place and therefore easily accessible [33].

10.3 Analysis of IVR-Based Interactive Visualization

We aim to be toolsmiths [4], adopting the problems that scientists in other disciplines have and using them to drive our research to create effective visualization and interaction tools. To measure progress we gathered data from anecdotal and formal evaluations. Results from several of our studies are reported below. More thorough discussions of our evaluations can be found in the papers cited in this section.

10.3.1 Anecdotal Findings

Below we report anecdotal feedback on several systems described above. This feedback is from domain scientists and we believe indicative of relevant properties of the systems, but due to its informal nature none of the results should be considered statistically significant in the sense of traditional formal evaluative experiments.

10.3.1.1   ARCHAVE

Over the course of several years four different versions of ARCHAVE were used by archaeologists to analyze data collected at the great temple site in Petra, Jordan. The prototyping and development process is described in [40]. The evaluation process is further described in [1]. Relevant results from those works are summarized here.

The evaluation process helped confirm the value of an immersive spatial visualization of the excavation record and also suggested a number of directions for improvement. One experiment involved two researchers who were interested in studying lamp and coin finds. We found that users performed three categories of tasks: queries of site information to generate and explore hypotheses, site exploration and pattern finding, and visual confirmation of hypotheses generated on-site.

Feedback suggested that their use of the system changed their mental model of the site as compared to participating in the excavation and searching the excavation data via a desktop database interface. They were also able to identify patterns in the finds that had not been identified during the excavation or found using the earlier online tools. They were enthusiastic about having IVR available, especially if it were extended from the prototype stage to cover more types of artifacts.

10.3.1.2   Diffusion MRI Visualization

We performed two experiments motivated by our brain visualization research. The results summarized here are also reported in [11]. The first experiment was an anecdotal comparison of Fishtank VR with our Cave. Overall, participants reported several advantages for the Cave, including its size, the larger field of view, the ability to interact more expressively with gestures, and the ability to walk around. They also noted several advantages of Fishtank VR, including sharper, crisper imagery, a more compact display, less noticeable claustrophobia, and a better ability to support collaboration. Four of the five participants subjectively preferred Fishtank VR.

Our second experiment evaluated the accuracy and speed of participants in performing a visual search task. In addition to comparing Fishtank VR and the Cave, it included in the comparison a reduced-resolution fish tank configuration that better matched the resolution of the Cave. Our findings were that users were more accurate and faster using the Fishtank VR configurations than using the Cave.

While both of these experiments seem to favor Fishtank VR, we believe that this is not only application-specific, task-specific, and also unduly influenced by the visual attributes of the configurations. With a significantly brighter and higher resolution Cave configuration that came much closer to matching those two key attributes of the Fishtank VR system, many of the differences would likely disappear. The particular visual search task that we used was a spatially localized one. With tasks that benefit from more contextual information, such as architectural walk-throughs, the surround-screen configurations are very suitable. Some of the other scientific applications that we report on share the need for spatial context that the Cave configuration can provide.

10.3.1.3   VOlume eXplorer

Over a period of three years, the VOX system was used extensively by the research community at Brown and our collaborators at peer institutions. We have collaborated closest with Brown Professor Kristi Wharton who researches developmental biology. A stereo-capable desktop version of VOX has been setup in her lab and now almost every dataset acquired is viewed with it to verify the scan is high enough resolution and quality to give a clear answer to the experimental question of interest, as well as for the analysis itself. Biologists walk the 10 min to the Cave building to view virtually all spatially complex datasets with "CaveVOX." Professor Wharton reports it is extremely useful to explore datasets in more detail and her group uses the Cave to draw conclusions from the data. To help make the immersive 3D data analysis experience more readily available to a greater number of biologists we will in early 2008 deploy with University support a head-tracked, stereo display (specifically, a stereo-capable Samsung 50″ DLP HD TV) in the University's biology imaging department. This scaled down version of the "Cave experience" will run the same VOX software on the Samsung display and sit side-by-side with conventional desktop analysis tools, easily accessible to dozens of research groups gathering 3D volume data, and is a direct result of the impact CaveVOX has made on researchers studying volume datasets. In this section we highlight specific instances where VOX was used for scientific investigations.

Our collaborators utilize VOX's advanced rendering capabilities to effectively visualize large datasets from laser scanning confocal microscopy. Visualization in IVR additionally helps them in fully appreciating the complexity (spatial and multi-channel) of the datasets. Over the past three years, our scientific collaborators have examined hundreds of datasets in the Cave. On several occasions, important observations have been made which had gone un-noticed on the desktop platform. Some instances of such observations have been accurate estimation of number of co-localizations in specimens. Co-localization is a phenomenon wherein multiple dyes fluoresce in the same voxel (the same voxel contains red and green expression, hence resulting in a yellow colored voxel). Conventional 2D image-based techniques tend to flatten the stack of images; hence even if there are disparate red and green pixels, but then happen to be along the same line-of-sight, one observes a yellow pixel. A 3D interactive visualization easily and efficiently eliminates this false count.

Similarly, discovery of experimental acquisition problems was facilitated by IVR. Problems with intensity falloff (as the laser signal optically penetrates a thick sample) are not apparent in comparison of subsequent 2D images, but a 3D stereoscopic visualization greatly assists in perceiving the falloff. In one instance, a problem was discovered with the way in which experimental samples were being placed on the slides – the slides were flattening the samples; hence the aspect ratios of various organs were inaccurate. Again, this flattening was not obvious from a 2D representation, it was only when the data was viewed in a 3D environment that the problem became obvious and the experimental setup was corrected.

A series of detailed quantitative analyses were performed in the Cave on zebrafish embryo datasets. We now discuss two such analyses which were impossible to do on a 2D desktop system but were made possible because of IVR. Bilateral symmetry in zebrafish is broken during early embryonic development. Key players in this process are cells with tiny hair-like structures, called cilia, which line the inside of a fluid-filled vesicle. The cilia are motile and generate a counter-clockwise flow of fluid in the vesicle. In turn, this counter-clockwise flow of fluid is important for left-sided development of the heart and left-sided gene expression in the developing brain. Visualizing the vesicle structure in a Cave allowed the researchers to "step inside" a magnified vesicle and study the structures within. In their words, "We were puzzled how a sphere could generate a directional flow. The data sets in the Cave revealed a local patch of cilia and suddenly the generation of a counter-clockwise flow of fluid started to make sense." Researchers then proceeded to make quantitative measurements on the distribution of cilia. This task was nearly impossible to do on a conventional desktop system; the Cave version helped the researchers to quickly process over 50 datasets. The result was an important discovery of an asymmetry in the cilia distribution which explained the asymmetric fluid flow [19].

Another set of investigations with zebrafish embryos was directed towards quantifying the branching structures of neurons (see Fig. 10.9). In order to propose a reasonable model it was important to make the measurements on a large population. Again, the Cave was used to process over 50 datasets effectively in a short period of time. Researchers said they used the Cave system because doing the same analysis of branching structures at the desktop was very hard. The results of the investigation are currently being processed [20].

10.3.1.4 ADVISER

ADVISER is impacting geoscience at Brown University. Over 20 geoscience publications have used it in data analysis. While no formal evaluations have been
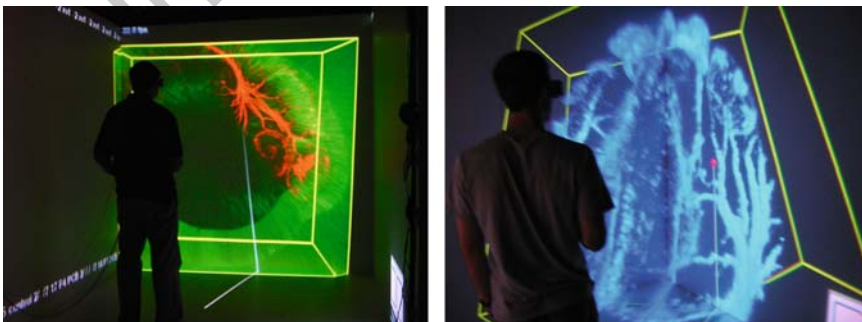

Fig. 10.9 Biologists examine neuronal branching structures in two different zebrafish embryo datasets. The task is to count the number of primary, secondary and tertiary neuronal branches for a population of zebrafish embryos

published on the system yet, we report here a general and specific application of the system with feedback from geoscientists. For further reading, please see [15, 18].

General Application: Going Virtually into the Field

A fundamental capability of ADVISER is allowing the free exploration of a 3D environment. Professor Jim Head has decades of geoscience research experience and reports moving through a 3D environment makes it easier to understand an environment's intricacies than simply studying a 2D map. In this way, ADVISER has been used to explore 3D environments for both research and education. Researchers have explored Mars with ADVISER to:

• stand inside craters and consider illumination and solar insulation leading to formation and preservation of ice deposits,
• assess polar layered deposits caused by the planet's recent climate change,
• plan and review candidate rover traverses for a proposed NASA mission to Mars's North Polar cap, and
• analyze a simulation of the Martian atmosphere.

Geoscientists doing field work in Antarctica's Dry Valley region (which has geological characteristics similar to some areas of Mars) previewed geographic, geological, and safety aspects of their trip using ADVISER. After the field trip, ADVISER was used to review at once data collected over multiple trips to the Antarctic Dry Valley and helped resolve problems that emerged in the field.

Instructors have used ADVISER to teach introductory-level courses as well as graduate seminars. In "Geological Sciences 5: Earth, Moon, and Mars" over 100 students per year study Mars, choose an area of it to pursue a specific scientific question, and then use ADVISER to visit Mars and work to answer their question. All students report the ADVISER assignment gives them new insights into the geology and topography of Mars and a greater appreciation for its spatial relationships. One student commented about ADVISER, "It's like going to a foreign country rather than reading about it in a book!"

Specific Application: Strike and Dip

The North Pole of Mars has layered terrain composed of water ice and dust. The individual thickness and brightness of layers are clues to the planet's recent climate record. Furthermore, layer spacing and 3D relationship to other layers are important for understanding their emplacement and evolution. ADVISER can overlay high resolution Mars Orbiter Camera data (which reveals alternating dust and ice layers) over Mars Orbiter Laser Altimeter topographic data in order to calculate each layer's thickness and geometry. A recent hypothesis states ice and dust layers encode a distinctive climate signal related to orbital parameter variations – similar to periodic changes in obliquity and eccentricity that cause ice ages on Earth. Strike and Dip

measurements performed in ADVISER with a "virtual field toolkit" describe subsurface layer orientation and structure. The geologist uses tools to identify multiple exposed points along a particular layer and compute best-fit planes from the points. A standard calculation produces the strike-and-dip measurements and can reveal whether the layers are flat or distorted beneath the surface. The value of IVR for strike and dip calculations lies in the significantly higher confidence geoscientists have when identifying a series of points belonging to the same layer. With conventional monoscopic displays of satellite data (a popular approach to visualizing and then labeling layers) there are frequent ambiguities due to interactions between the reflectance of surface material and shading from topographic features. These situations can be easily resolved using ADVISER to drape high-resolution satellite imagery over high-resolution topological data and interactively view the area quickly from several vantage points.

10.3.2 Formal Evaluations

In this section we report results from formal studies designed to measure some aspect of the systems and carefully control for other variables. Subjects were recruited and paid to participate in the studies. Standard statistical methods were applied when analyzing the collected data. The experiments we summarize in this section have all been published elsewhere and their details can be found in citations below.

10.3.2.1   VOlume eXplorer

Following our positive anecdotal experience with developmental biologists in their use of VOX in the Cave and the positive scientific return, we wanted to see if the Cave statistically differed from other technologies and conducted a formal evaluation which would mimic the relatively free-form scientific exploration of datasets by these scientists. This is in contrast to most participant studies which focus on interaction techniques, presence and usability. In such studies, participants are typically asked to perform relatively simple "benchmark" tasks. In this study, we focused on free-form exploration of scientific data without emphasis on speed/accuracy performance tradeoff. We use an open-ended "think aloud" protocol which encourages participants to explore and talk about their exploration without any constraints.

Twelve users, all familiar with confocal datasets; participated in the study. All users explored the Desktop, Fishtank VR and Cave environments in random orders; and underwent a brief training phase on each platform. Once users indicated that they were comfortable with the interaction; they proceeded onto the testing phase. During the testing phase participants explored confocal datasets; talked about their observations and responded to questions about each dataset. After the testing phase, users were asked to choose a single platform (out of the three) and examine two

more datasets. Following this, users filled out a post-questionnaire which noted their quantitative responses on a Lickert scale. A debriefing at the end helped us collate their subjective responses.

The selected tasks involved looking at real confocal datasets from the egg-chamber, brain, and gut regions of a fruit-fly (see Fig. 10.10). An expert biologist assisted us in preparing the datasets and a list of exhaustive features that were present in the data. A table with questions related to features and a weight associated with each question was also determined in advance by the expert. The questions and tasks were inspired by real-life analogues; the tasks emphasized understanding spatial relationships including characterizing the general features in a volume, identifying co-located features, and reporting geometric relationships in the datasets. Performance of participants was assessed based on a review of the videotape of each session. Participants were awarded points based on their observations in accordance with the table prepared by the expert.

Prabhat et al. [29] presents detailed results from the study; we only highlight the major results in this section. All significance results presented in this chapter were conducted with ANOVA at 5% level of significance. Briefly, we found that users performed significantly better in platforms with higher levels of immersion (Cave > Fishtank VR > Desktop, $p < 0.0001$). All twelve participants chose the Cave (over the Fishtank VR or Desktop) when presented with a choice to continue exploration on new datasets. In the post-questionnaire, participants generally rated the Cave higher than Fishtank VR and Desktop for a range of metrics (learning about datasets, answering specific questions about datasets, confidence in finding features, etc.). While the Cave was rated slightly higher than the Fishtank VR configuration, it should be noted that the Desktop was very poorly rated across all metrics. When asked to list major advantages and disadvantages of the various platforms, participants subjectively rated the Cave highly for its large display area, wide field of view and its immersive capabilities. They subjectively liked the clarity and crispness of the Fishtank VR display, but complained of the small size and FOV. All users disliked the desktop and complained of the lack of stereo. Everyone acknowledged the inferior brightness of our current Cave (as compared to Fishtank VR and Desktop), and yet they preferred the Cave for its immersive capabilities.

Fig. 10.10 Experimental setup for the exploring scientific datasets. Scientists examine a range of datasets on a conventional desktop (left), Fishtank (middle), and Cave (right) environment. (Note: different datasets are shown on each display in these images.)

Building on the results from the study reported in earlier section, we decided to restrict the range of tasks and come up with focused tasks. We did not want to lose the relevance to domain science analysis conducted by scientists; hence we chose three tasks motivated by real problems that neuroscientists need to tackle. An expert neuroscientist prepared datasets for this study. We chose to examine neuronal datasets; the tasks were to:

- count the number of spines along a dendrite
- count the number of contact points between multiple axons and dendrites
- count the number of pyramidal neurons (see Fig. 10.11).

An identical protocol (as reported in the last experiment) was used. Twelve subjects, this time with varying background in neurosciences, were recruited for the tasks. Users went through a training phase where they were exposed to a sample neuron dataset; they then performed the three tasks on unique datasets. All platforms were presented in random order. After the testing phase; subjects were asked to move to a neutral location and choose a platform for performing the three tasks on new datasets. Subjects then chose a platform, conducted the tasks and finished up the experiment with responses to a post-questionnaire followed by debriefing.

Sanchez et al. [32] reports on the detailed results from the study. In brief, we found similar trends to the results for the developmental biology study. Users rated the Cave higher than Fishtank VR, and Fishtank VR higher than the Desktop system. There were a few differences in the choice phase though. For spatially complex tasks (such as finding contact points between axons and dendrites) most subjects chose the Cave over Fishtank VR and the Desktop. For counting the number of spines, the same held true (most subjects preferred the Cave). But for counting the number of pyramidal neurons, subject responses were mixed. There was no clear preference between either the Cave or Fishtank VR.

10.3.2.2 ADVISER

The ADVISER system (described in the previous section) was applied in an educational outreach setting. We incorporated the system into an undergraduate laboratory exercise and evaluated the usefulness of the system. In the exercise,

Fig. 10.11 Experimental setup for performing specific scientific tasks. Users examine a neuron dataset on a desktop (left), Fishtank (middle), and Cave (right)

Fig. 10.12 Student using the ADVISER system to explore the surface of Mars

undergraduate students gather information and insights while exploring the Martian surface in a computer-rendered immersive virtual reality system (see Fig. 10.12). Students choose an area on Mars for virtual exploration, formulated geological questions, and pursue their investigation using a real-time 3D terrain exploration tool. Ninety students completed a follow-up survey and reported that using a conventional desktop and our Cave contributed significantly to the learning experience, and that they would choose the immersive environments over standard 2D maps in the future exercises.

In general we observed that students highly prefer a Cave-like system to a conventional desktop display for learning about topography datasets (ANOVA $F = 11.594$, $p < 0.0001$). This preference is indicated by their ratings and choice of Cave as the preferred medium for future exploration. Both Cave and desktop media are preferred, however, to a standard 2D image based investigation ($F = 29.91$, $p < 0.0001$). Students' subjective responses are positive about the insights gained from the Lab exercise; we consequently believe that 3D visualization is a valuable tool in teaching students about topographical and geological datasets.

10.4 Summary

In this chapter, we have presented a variety of different IVR-based interactive visualizations systems developed at Brown University. These systems provide support for scientists in archaeology, computational fluid dynamics (CFD), biology, and the geosciences. By working directly with these scientists, we have been able to show, both anecdotally and formally, that IVR-based visualization systems have important benefits that enable scientists to do their jobs better. The systems we have developed in the Cave have provided insights, in some cases, that would not have otherwise been discovered or would have taken a significantly longer time.

We are observing that IVR is making a positive impact on visualizing scientific data with complex 3D spatial relationships and also provides significant benefit to

some tasks where magnifying the projection of the data helps find features faster or otherwise not seen. Body-centric interaction appears to be another important component of IVR's benefit. However, understanding when and why IVR applies generally remains an area of active research, and there is no clear-cut formula for when IVR is the right tool. It is generally necessary to try visualizing your data in IVR, and potentially tailor an interactive visualization to your particular needs.

The reader should bear in mind that our old Cave system was built in 1998 and is much dimmer than a conventional desktop display; the spatial resolution is also much lower (10 dpi, whereas we estimate 25–30 dpi would make it comparable to a typical 72 dpi desktop monitor because the Cave wall surfaces are viewed at a greater distance than a desktop screen). Still, the Cave outperformed Fishtank VR and conventional monitors in many situations. We think the greatest advantage will come from a brighter display that reveals a comparable dynamic range of visual data, and that, as the spatial complexity of data increases, higher resolution would result in greater benefit. Modern projectors already provide very high brightness display, and tiling them is a standard approach now for achieving higher resolutions.

Biologists and geoscientists at Brown, as a result of our initial collaborations, are installing head-tracked, stereo-capable displays in their buildings. While single walls are not fully immersive environments, these conveniently located systems coupled with other research tools are a significant step towards production use of immersive virtual reality for these scientific domains. We intend to continue partnering with scientists at Brown and elsewhere who are struggling to understand their data both in the early stages, like many of the projects reported here, and later with systems deployed in their laboratories where their daily work takes place.

Appendix: IVR Hardware Configurations

One of the key characteristics of IVR is that special hardware is needed beyond the traditional desktop computer (i.e., monitor, keyboard, and mouse) to support the high level of immersion and more fluid interaction that benefits IVR-based interactive visualization. There are a variety of different input and output hardware configurations that can be employed in these applications, and, in this appendix, we will briefly discuss ones we have worked with over the years. A thorough discussion on IVR input and output devices can be found in [3].

A.1   Display Configurations

In many cases with interactive visualization virtual environments (VEs), we want to present users with a head-tracked stereoscopic display so they can see visualizations in immersive 3D with appropriate motion parallax. A tracking system is required to create motion parallax when users move in the VE, and these devices

are discussed in the next section. For the stereoscopic display, there are several different types that can be used.

A.1.1   Monitors

Conventional monitors coupled with a pair of stereo glasses makes for a simple yet effective visual display for interactive visualization applications. When a user is head tracked this configuration is commonly referred to as "Fishtank VR" [43]. These configurations are relatively inexpensive compared to other visual display devices, such as workbenches and surround screen devices, and provide excellent spatial resolution. However, monitors are not very immersive and the user has a very limited range of movement due to its small field of regard (FOR), the amount of physical space surrounding the user in which visual images are displayed.

A.1.2   Surround-Screen Displays

A surround-screen display is a visual output device that has three or more large (anywhere between 8 to 12 feet in width and height) projection-based display screens that surround the human participant (often referred to as a CAVE™ [10]). They provide high spatial resolution, a large FOR and a large field of view (FOV), the maximum number of degrees of visual angle that can be seen instantaneously on a display. This high FOV lets users leverage their peripheral vision. As with a monitor, surround screen devices provide stereopsis with stereo glasses. Additionally, real and virtual objects can be mixed in the environment.

   One of the biggest disadvantages of surround screen display devices, as well as any projection-based display system, is that user can have difficulties seeing objects in stereo under certain conditions. When the user gets close to the display or when objects appear to be right in front of the user, it becomes more and more difficult for a user to fuse the two images together. Eye strain is a common problem in these situations. Another issue is the physical/virtual object occlusion problem. The problem arises when the user tries to move a physical object behind virtual objects. Although a user can physically move an input device behind a graphical object, visually, the device will appear in front of the graphical object, since it is actually being projected on the screen. This is a common problem with any projection-based display device (or Fishtank VR configuration) and can hinder the immersive experience and break the 3D illusion produced by stereo.

A.1.3   High-Resolution Display Walls

High-resolution display walls (e.g., tiled display surfaces) are becoming increasingly popular for interactive visualization applications. Display walls can be constructed by combining several LCD screens or projectors. These displays offer greater

image fidelity than other immersive and desktop displays because the increased number of pixels displayed over a large area can fill most of a user's FOV. For example, Princeton University developed the Scalable Display Wall (18 feet long and 8 feet high) with a resolution of 6,000 by 3,000 pixels using 24 projectors [41]. Other examples can be found in [27]. High-resolution display walls have many of the same benefits and problems associated with surround screen displays in terms stereo image fusion, FOV, and the physical/virtual object occlusion problem. Since high-resolution display walls do not surround the user with visual imagery, they have a much smaller FOR compared to a surround screen device.

A.1.4   Workbenches

Another type of projection-based display is the Responsive Workbench™, originally developed by [21]. In general, workbenches make for an intuitive display for certain types of applications. Relative to surround screen displays, workbench screen sizes are smaller, which improves visual quality. In many device designs, the display can be rotated so the screen's orientation relative to the user is anywhere from completely horizontal to almost vertical, making the device quite flexible.

In general, users have limited mobility when interacting with a workbench because the display is not head coupled like a head-mounted display (see below) and does not surround them in a room-sized display. Therefore, as with monitors, the range of viewpoints from which a user can see 3D imagery is restricted since, for some viewpoints, all or part of the screen would not be visible. For example, it would not be possible for a user to see the bottom of a stationary, graphical object by physically looking underneath it, since the display surface would no longer be in the user's FOV thus breaking the 3D illusion.

A.1.5   Head Mounted Displays

Thus far we have focused on stationary displays (i.e., visual devices that do not move with the user). Here, we will discuss visual displays where the user is attached (i.e., head-coupled) to the display device. Head-coupled display devices used for IVR-based interactive visualization is the head mounted display (HMD). A head mounted display's main goal is to place images directly in front of the user's eyes using one (for monoscopic viewing) or two (for stereoscopic viewing) small screens. Since, the screens may or may not be placed directly in front of the user's eyes, a combination of refractive lenses and/or mirrors (depending on the optical technique used) are used to present and sometimes magnify the images shown to the user.

One of the biggest advantages of HMDs is that the user can have complete physical visual immersion (i.e., a 100% FOR) since the user always sees the virtual world regardless of head position and orientation. Even though HMDs have a 100%

FOR, many of them have small FOVs (i.e, between 30 and 50 degrees in horizontal or vertical) which can cause performance problems. Even high-end HMDs have limited FOVs when compared to surround screen displays. Since the real world is completely blocked out of the user's view, interaction while wearing an HMD usually requires some type of graphical representation of either one or both hands or the input device used. These graphical representations can be as simple as a cube or as sophisticated as a hand model containing thousands of polygons. HMDs also put a strain on the types of input devices that can be used since the user cannot physically see the device in order to use it. HMDs are more claustrophobic than the other types of displays because they do eliminate all real world cues, and unless trackers are wireless, also have entangling cords that add to the cumbersomeness, weight and discomfort of HMDs for prolonged work sessions.

A.2   Input Device Configurations

In IVR-based interactive visualization systems, users can use stereoscopic displays to see and interact with their data spatially in 3D. Thus, VEs afford a much greater variety of interaction capabilities than a traditional desktop computing environment. There are many different types of input devices that can be used in an IVR-based interactive visualization application, and, in this section, we briefly discuss the most common devices.

A.2.1   Motion Trackers

Motion tracking devices are one of the most common and fundamental interaction devices used in VEs. Since they can track different parts of a user's body, they provide a critical piece of functionality in terms of head, hand, and device tracking. Head tracking is important for motion parallax and providing the correct stereoscopic viewpoint as users move around the VE, while hand and device tracking is important for users to interact with data spatially in six dimensions (three translation and three rotation degrees of freedom).

There are a variety of different tracking systems and technologies used in VEs today and they all have advantages and disadvantages [45]. For example, *magnetic trackers* have good range, and are generally accurate to within 0.1 inches in position and 0.1 degrees in orientation, but any ferromagnetic or conductive objects present in the room with the transmitter will distort the magnetic field, thus reducing the accuracy. *Acoustic trackers* are relatively inexpensive and lightweight, but often have a short range, low sampling rates (compared with optical and inertial trackers which can have sampling rates above 1 KHz), and their accuracy suffers if acoustically reflective surfaces are present in the room.

Inertial trackers use a variety of inertial measurement devices such as angular rate gyroscopes and linear accelerometers. These devices can produce measurements at high sampling rates but suffer error accumulation from sensor biases, noise, and drift. *Optical trackers* use computer vision techniques and optical sensors such as cameras and infrared emitters. They often suffer from the occlusion problem because they sometimes cannot pick up information about parts of the user's body that are occluded by other parts. Finally, *hybrid tracking* attempts to put more than one tracking technology together to help increase accuracy, reduce latency, and, in general, provide a better virtual environment experience. For example, combining inertial and acoustic tracking or inertial and optical tracking technologies have been successful in providing robust tracking solutions. The major difficulty with hybrid trackers is that the more components added to the system, the more complex the device becomes.

A.2.2   3D Mice

In many cases, tracking devices are combined with other physical widgets such as buttons, sliders, knobs, and dials to create more functionally powerful input devices. These *3D mice* are hand held or worn input devices which combine motion tracking with a set of physical interface widgets placed in various configurations.

The distinguishing characteristic of 3D mice opposed to regular 2D mice is that a user physically moves them in 3D space to obtain position and/or orientation information instead of just moving the device along a flat surface. Therefore, users can hold the device or, in some cases, wear them. Additionally, with orientation information present, it is trivial to determine where the device is pointing (i.e., the device's direction vector) which is used in many fundamental 3D interaction techniques for working with visualization data where it is useful to be able to point at specific locations in three-space. These devices can also be considered 6D mice in many cases because they often provide both 3D orientation and 3D position information. Because of their general applicability, they can be mapped to many different interaction techniques, and, in one form or another, they are often the primary means of communicating user intention in 3D interfaces. A variety of these devices have been developed over the years including the "bat" [42], Ascension Technology Corporation's Wanda, and the FingerSleeve [47].

A.2.3   Other Input Devices

A variety of other input devices can be utilized in IVR-based interactive visualization applications. For example, data gloves that sense a user's finger motion can be used to grab virtual objects and manipulate data. Joysticks and gamepads such as the Xbox 360 or Nintendo Wii controllers can be used in these environments as well.

Finally, pen-based tablets such as Tablet PCs and PDAs can be used in IVR-based visualization applications. These types of devices are becoming increasingly popular in both desktop 3D and in VE applications because they give the user the ability to interact with a "pen and paper" interface and bring 2D interaction techniques such as handwriting and menu-based techniques into 3D immersive environments [13, 15].

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