Virtual reality in behavioral neuroscience and beyond

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Virtual reality (VR) has finally come of age for serious applications in the behavioral neurosciences. After capturing the public imagination a decade ago, enthusiasm for VR flagged due to hardware limitations, an absent commercial market and manufacturers who dropped the mass-market products that normally drive technological development. Recently, however, improvements in computer speed, quality of head-mounted displays and wide-area tracking systems have made VR attractive for both research and real-world applications in neuroscience, cognitive science and psychology. New and exciting applications for VR have emerged in research, training, rehabilitation, teleoperation, virtual archeology and tele-immersion.

Scientists have often looked to *Star Trek*™ for inspiration. Although transporters and warp drive are things of the future, 'communicators' (cell phones) and 'tricorders' (PDAs) are commonplace. Some of us have even taken the lead from another *Star Trek* (*The Next Generation*) innovation: the Holodeck. For those who are not 'Trekkies', the Holodeck is a large room on the starship *Enterprise* that can immerse members of the crew in almost any imaginable environment, such as 18th century London or the 5th moon of the planet Jupiter, by creating the illusion that they are someplace other than where they really are. Although 21st century technology does not allow the level of realism portrayed in *Star Trek*, new research methods relying on virtual reality are changing the way we study the mind and brain, as well as how we apply the fruits of this research in the 'real world'.

"It is not true that the laboratory can never be like life. The laboratory *must* be like life!" exclaimed the eminent perceptual psychologist J. J. Gibson[1] in 1979. Inspired by this philosophy and by improvements in technology, we and others have created virtual reality laboratories to investigate how humans interact with their surroundings under more realistic conditions. Gibson's 'ecological' approach argues that the process of perception emerges from an organism embedded in and interacting with its environment. This concept is realized in the VENLab (Virtual Environment Navigation Laboratory) at Brown University, which provides a unique immersive experience that facilitates new possibilities in behavioral research on vision and action[2] (http://www.cog.brown.edu/Research/ven_lab).

Technological advances

The VENLab is one example of the application of virtual reality to behavioral neuroscience. After years of hype[3], virtual reality is finally living up to its promise as more powerful computer graphics systems, better display technologies and useable software packages facilitate the creation of affordable virtual reality facilities without Disney-sized budgets[4]. What these applications have in common is the goal of creating a virtual reality system that allows both precise control over stimuli (the virtual world) and the experience of a realistic interactive environment.

Although there is no 'off-the-shelf' solution for creating a virtual reality system, there are several elements that make today's virtual reality systems better than those of only a few years ago. First, the observer can move freely and have the system respond to his/her actions in close to real time. This is essential because a delay between a user's actions and consequent changes in the virtual world not only destroys one's sense of being embedded in a 'real' environment, but can actually lead to physical disorientation and nausea[5]. Second, displays typically fill a significant portion of an observer's field of view and provide a sense of 'embeddedness'. Third, systems are able to display multiple three-dimensional objects with realistically shaded and textured surfaces.

A variety of virtual reality approaches are available, ranging from relatively inexpensive systems to large immersive installations. The most common is 'desktop virtual reality', in which a high-quality graphics workstation displays a virtual environment on a standard computer monitor (as in computer games such as "Doom"). Such desktop systems do not generally allow the user to interact naturally with the virtual world, as control is typically limited to a mouse or joystick. Consequently, these systems fail to provide an immersive experience—the illusion that one is actually in the virtual environment.

The earliest application of immersive virtual reality was the driving or flight simulator. Such systems extend desktop VR to a large front-mounted projection screen with a display that is updated in response to realistic controls such as a steering wheel and dashboard, or bicycle handlebars and pedals[6,7]. A second variation is the Immersadesk®, developed at the University of Illinois at Chicago (http://www.evl.uic.edu). It achieves a sense of immersion with a very large projection screen (about 110° of the visual field), a stereoscopic display and a head-tracking system that updates the display in response to natural head movements. However, the user has a very limited range of motion and must face forward to view the virtual environment.

The next step toward full immersion is the CAVE™, a four-walled virtual reality system[8] also originally developed at the University of Illinois at Chicago. A CAVE™ is a three-meter square

Fig. 1. The VENLab at Brown University is a 40' × 40' immersive virtual reality space. An InterSense IS-900 head tracker is used to measure head position in real-time. The virtual environment is presented through an 80° field-of-view head-mounted stereo display driven by a graphics workstation.

chamber with projection screens on the walls, floor and ceiling, yielding a strong sense of immersion. The display is typically stereoscopic and updated with a head-tracker and hand-tracker, allowing the user to make natural movements within a surrounding virtual environment. However, the range of movement is still somewhat circumscribed.

For many applications, including behavioral neuroscience, the goal is to create a controlled environment that is as life-like as possible[9]. For example, in our own work we are interested in how humans learn routes to get from one place to another. At least three sources of information are available to us: visual information in the form of optic flow[10], visual information about objects that may serve as landmarks, and the body senses that tell us about self-motion (including vestibular and proprioceptive information). Teasing apart these contributions requires that subjects actually walk through an environment. Yet this environment must be controllable so that information about optic flow and landmarks may be manipulated. Easy to accomplish with a rat, bee or ant, but much harder with a human subject!

Such questions can only be answered by creating a highly immersive virtual environment such as the VENLab[2]—which we believe to be the largest walkable immersive virtual reality system in existence for scientific research (**Fig. 1**). This system is composed of a highly accurate wide-area head tracker (IS-900 from InterSense Corporation, Burlington, Massachusetts; http://www.isense.com), a high-end graphics workstation and a wide field-of-view (80°) stereo head mounted display (HMD) to display the virtual environments. With a baffle blocking out any view of the real world, most subjects report feeling entirely present in the world we create for them. They rarely, if ever, have any sense of where they are in the physical room and respond appropriately when faced with 50-foot cliffs, spinning tunnels and carousels (**Fig. 2**). Indeed, some subjects absolutely refuse to approach the edge of the cliff, let alone walk across one of the plank bridges provided for them. Even though the resolution of our HMD is only moderate—640 × 480—the sense of realism is high. We attribute this to three properties of the VENLab: the speed with which the display is updated in response to a subject's movements, the wide field-of-view of the HMD and the use of the subject's natural physical movements (as in the real world) to produce changes in the virtual environment.

Scientific and applied uses of virtual reality

From a research point of view, systems like the VENLab provide an ideal tool for studying human behavior. For example, we tested whether people rely on optic flow or egocentric position to guide locomotor behavior to a goal by presenting physically impossible motion patterns to walking observers[11]. Subjects relied on both types of information, but made more use of optic flow information when it was available. We have also measured the degree to which homing behavior is based on visual information versus the body senses by manipulating the visual information for self-motion[12]. In this case, we found that although subjects used optic flow, they relied more on information from body senses when available. Finally, we probed the geometry of cognitive maps by having subjects explore the 'Secret Garden'—a hedge-maze environment containing realistic places (a fountain, a statue and so on). Subjects learned the layout by freely walking around (**Fig. 3**). It was then covertly distorted—by stretching the world to alter distances, or shearing it to change angles—to assess how these properties contribute to navigation (M.C. Harrison, W.H.W. & M.J.T., unpublished data). Thus far, the ordinal structure of the environment, rather than metric distances and angles, seems to dominate navigation behavior.

In each of these examples, the critical element provided by virtual reality is the ability to break the laws of optics and physics, or to disconnect physical reality as specified by a subject's body senses from the world he/she is seeing. As such, virtual reality offers a unique research tool that allows the behavioral neuroscientist an opportunity to address heretofore unanswerable questions.

Virtual reality is being used to similar advantage in many domains outside the research environment. In contrast to our use of virtual reality to study human behavior, many 'real-world' applications of virtual reality involve modifying human behavior. Most prevalent are flight and driving simulators that allow a hands-on experience without the risks associated with a novice controlling a rapidly moving vehicle. The goal of these and other simulators is to train individuals to operate complex machinery, to respond appropriately to rapidly unfolding events (such as

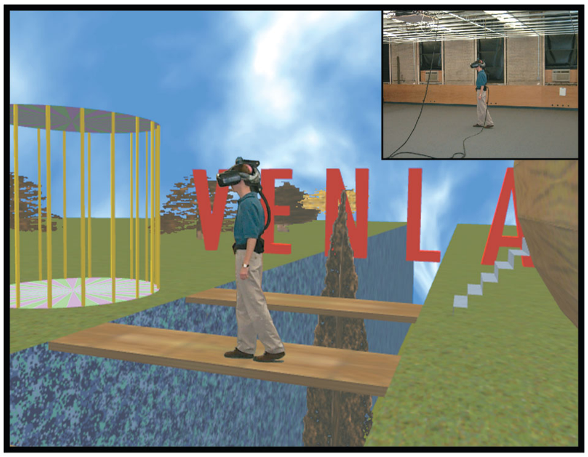

Fig. 2. The virtual environments presented in the VENLab provide a feeling of total immersion. Subjects are free to explore the entire virtual space, which changes in response to their movements. Stereo, motion parallax and other depth cues produce a true three-dimensional experience. Here a subject carefully crosses a 50' deep ravine.

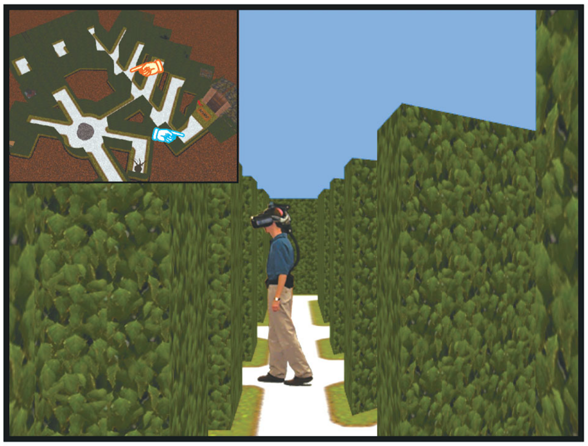

Fig. 3. An example of a complex 'secret garden' virtual environment created to study the mental representation of cognitive maps in humans. The red hand denotes the position of the subject, while the blue hand denotes the viewpoint from which this picture was taken. Adapted from M.C. Harrison, W.H.W. & M.J.T., unpublished.

'friend or foe' decisions for military personnel), or to function in interactive environments that would otherwise be too expensive or hostile to be used on a day-to-day basis (training astronauts or firemen). Such established uses of virtual reality are becoming both more widespread and more compelling (thereby enhancing training) with the introduction of new virtual reality technologies like those discussed above.

A second area where virtual reality has been used to modify human behavior is in the treatment of psychological and mental health disorders. Applications include the use of virtual reality in cognitive therapy, the facilitation of visualization in psychotherapy, and the special education of learning disabled children[13]. Other uses include presenting schizophrenic patients with virtual hallucinations in an effort to desensitize them to their actual hallucinations[14]. Although many of these applications are still highly experimental, one area where virtual reality may be of great help is in phobia desensitization[15]. The real-world implementation of a systematic desensitization procedure may be very difficult, depending on the phobia-inducing stimulus. For example, it would be non-trivial to arrange successive experiences with airplanes or with rattlesnakes. In the future, an immersive virtual reality system in the therapists' office could be programmed to present the stimuli associated with almost any phobia. Indeed, from our own experiences in the VENLab, we know that the experience of heights in immersive virtual reality can be very compelling. Fear of flying, fear of heights and other phobias have all been successfully treated in pilot studies[15–17].

Virtual reality may also be used to enhance human abilities rather than modify them. Tele-operation—remote control of a vehicle or robot with video feedback to the operator—is far more effective if the operator is immersed in the remote environment. Imagine feeling as if you were on Mars rather than remotely controlling a robot equipped with a video camera. Tele-operation has recently been used with some success in 'urban search and rescue' where remotely operated robots are placed in environments that are otherwise too dangerous or inaccessible for humans. Most notable was the use of a variety of robots from the University of South Florida in rescue efforts at the World Trade Center on September 11th, 2001 (http://www.csee.usf.edu/robotics/crasar). Virtual reality also has potential in the rehabilitation of patients with motor control deficits and, through augmented reality, enhancing the abilities of Parkinson's patients or paraplegics[18]. Someday it may be possible for a person to control a robot arm through a neural implant[19].

Not only can virtual reality take us to inaccessible places, but it can take us to places that no longer exist. Virtual archaeology is a research area of rapid growth in which virtual reality is used to reconstruct buildings from the past. For example, in the ARCHAVE (Archaeological Data Visualization in VR) project at Brown University (http://www.cs.brown.edu/research/graphics/research/sciviz/archaeology/archave), researchers are rebuilding the ancient middle eastern city of Petra[20]. The interactive and immersive nature of the reconstruction facilitates both better understanding of the layout of Petra and the discovery of new features of the city that might otherwise have never been revealed.

Virtual reality is being used for the construction of new buildings as well as old buildings. Three-dimensional computer graphics architectural models are already very common—virtual reality adds a new dimension by allowing the architect, contractor or customer to explore the proposed building before it is actually constructed. Such virtual walkthroughs may help avoid costly mistakes in structure, form and function—imagine if you were able to use the VENLab or a CAVE to walk through your house or lab before it was built. Similarly, virtual reality provides a new medium for collaborative design projects across geographically distant locations. Not only do users share a single virtual environment, but they share a common three-dimensional graphical workspace in which the design process can occur (http://www.advanced.org/tele-immersion). Similar technologies might be used in education to introduce students to significant historical sites or remote locations around the globe that would otherwise be impossible to visit—much like the 'Magic School Bus' of TV fame. One working version of this idea is the Virtual Reality Station in NASA's Mobile Aeronautics Education Lab. This HMD-equipped lab allows school children to experience docking the Space Shuttle with the International Space Station or taking a SpaceWalk (http://www.grc.nasa.gov/WWW/MAELVRSTATION).

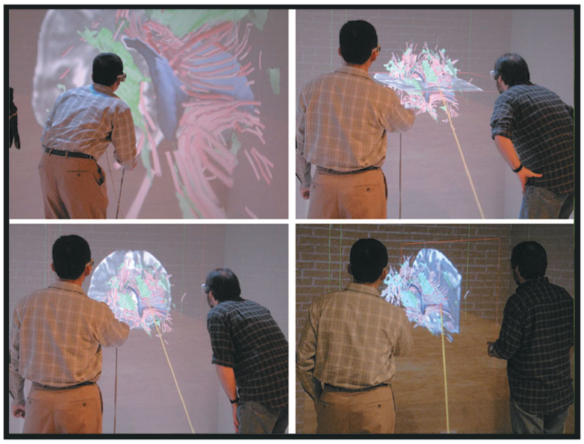

Fig. 4. Two users explore neural anatomy and the connectivity of the human brain using virtual reality (in a CAVE at Brown University). The images depict a geometric abstraction derived from tensor-valued water self-diffusion rate measurements made with MRI. From http://www.cs.brown.edu/research/graphics/research/sciviz/brain/brain.html.

Another place virtual reality can take us is inside the human body. Rather than viewing medical images as two-dimensional slices, users can actively explore three-dimensional volumes. This three-dimensional interactive aspect to virtual reality may facilitate the development of new drugs[21]. Similarly, three-dimensional reconstructions of organ and tissue structure, typically derived from MRI data, can be used in planning surgical procedures or disease diagnosis. For example, computer scientists at Brown University are collaborating with brain researchers to explore uses of virtual reality for better understanding of neural anatomy, development and pathology (**Fig. 4**). One application of this research is targeted specifically at pre-surgical treatment planning for brain tumors and has spawned new insights into how connectivity information in the human brain manifests in MRI datasets[22] (http://www.cs.brown.edu/research/graphics/research/sciviz/brain/brain.html).

Conclusions

Technological advances in virtual reality have opened up many new research possibilities and applications in behavioral neuroscience. As virtual reality technology matures, even greater potential exists for the controlled study and manipulation of the human organism under ecological conditions. One can envision a day when virtual reality systems like the VENLab will be relatively commonplace, offering interactions not only with places that no longer exist or never existed, but with avatars (virtual representations of individuals) of remote users or simulated characters—after all, Sherlock Holmes was a regular on the Holodeck.

Acknowledgments

The VENLab was funded by a Learning and Intelligent Systems (LIS) award from the National Science Foundation (IRI-9720327) to W.H.W., M.J.T. and L.P. Kaelbling (now at M.I.T.). We thank the students and postdocs who have collaborated with us on the VENLab over the years and D. Laidlaw for his contributions to this article.

RECEIVED 25 JULY; ACCEPTED 11 SEPTEMBER 2002

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