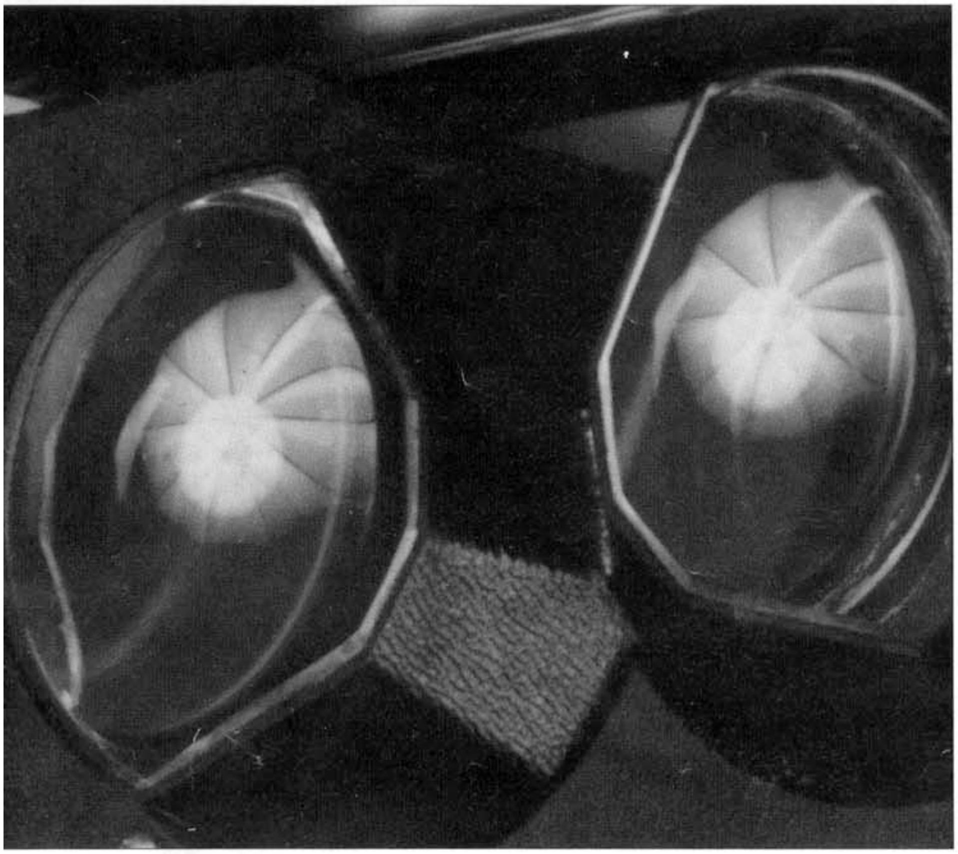
What Are Virtual Environments?



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Virtual environment displays arose from vehicle simulation and teleoperations technology of the 1960s. This article addresses some of the questions facing this technology and its commercial development.

Virtual environment displays are interactive, head-referenced computer displays that give users the illusion of displacement to another location. Different terms have been applied to the illusion. Some, like the oxymoronic "artificial reality" and "virtual reality," suggest much higher performance than current technology can generally provide. Others, like "cyberspace," are puzzling neologisms. Expressions like "virtual worlds" and "virtual environment" seem preferable because they are linguistically conservative, relating to well-established terms like virtual image. In fact, we can define virtual environments as interactive, virtual image displays enhanced by special processing and by nonvisual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic space.[1]

Why are these displays useful? Who uses them? How are they developed? This article addresses these and other questions related to this emerging technology.

Virtual environments as media

Virtual environment displays potentially provide a new communication medium for human-machine interaction. In some cases, they might prove cheaper, more convenient, and more efficient than former interface technologies. In fact, teleoperations-like tasks requiring coordinated control of a viewing position and a manipulator, as occur in laparoscopic surgery or surgical simulation, are the tasks most likely to benefit from a virtual environment interface. In teleoperation or planetary surface visualization, virtual environments offer techniques for solving control problems caused by time delays or awkward camera placements. Additionally, the completely synthetic character of purely virtual environments allows the introduction of visual, auditory, and haptic interaction modes totally unrealizable in physical environments.

Considered as communications media, virtual environment displays have broad applications potential—in education, procedure training, high-level programming, teleoperation, remote planetary surface exploration, exploratory data analysis, and scientific visualization, as well as entertainment. Furthermore, the potential usefulness of virtual environments in the scientific investigation of psychophysical, physiological, human factors, and perceptual questions has attracted physiological and cognitive scientists whose research should provide invaluable insight for improved designs of virtual environment interfaces.

Users and developers

Scientists, developers, and those with nonprofessional interests in virtual environment technology may be divided into two general groups: those who wish to use the technology to advance their particular profession or interest and those who wish to develop and perfect the technology itself. Unfortunately, the

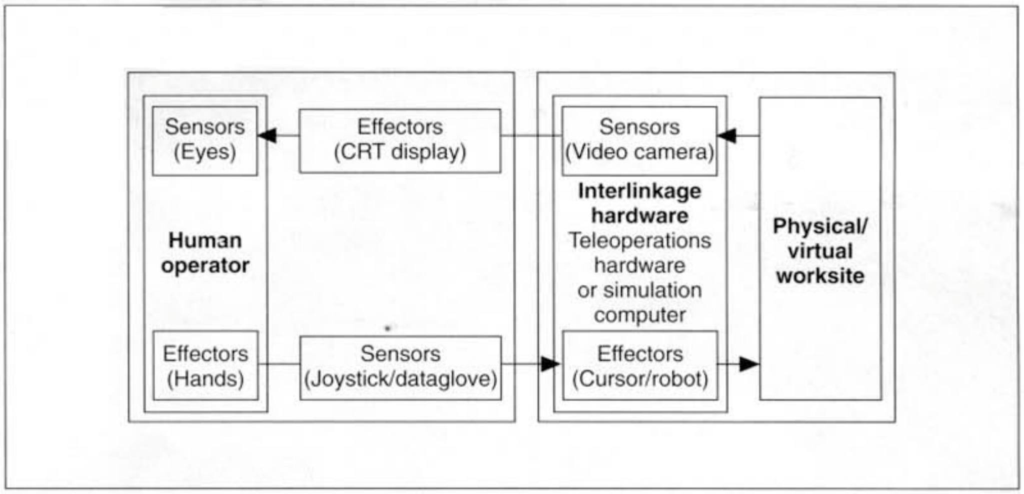

Figure 1. Functional breakdown of virtual environment or teleoperations systems.

hyperbole and sensational press coverage associated with some of this technology has led many potential users to overestimate the actual capabilities of existing systems. Many of them must actually develop the technology significantly for their specific tasks. Unless their expertise includes knowledge of the human-machine interface requirements for their application, their resulting product will rarely get beyond a "conceptual demo" that lacks practical utility.

Another remarkable aspect of activity in this area has been the flourishing of interest among nontechnical groups and lay organizations like the Meckler Foundation and the Education Foundation. Some of these groups have sponsored conferences or workshops that attract hundreds of people. Though these meetings have drawn some genuine developers, their variable content is underscored by a remark from one of the more enthusiastic proponents of "virtual reality," who claimed at the 1992 Meckler conference that VR was "a very special field where there are no experts, and everyone can be one."

Nothing could be more false. The research and development community associated with vehicle simulation and teleoperations interface development have the technical training and applications background required to design usable virtual environment displays and to constitute a tradition of expertise in this field. Virtual environments are best viewed as extensions of the technology discussed in courses like those periodically offered on flight simulation at Massachusetts Institute of Technology and State University of New York at Binghamton. Targeted workshops and conferences sponsored by national professional associations, such as the National Research Council, National Science Foundation, Engineering Foundation, NASA, and Office of Naval Research, have also been forums for experts in the technologies necessary to support virtual environments.

How virtual environments work

The illusory virtual environment is created through the operation of three types of hardware: (1) sensors, such as head position sensors, to detect the operator's body movements, (2) effectors, such as a stereoscopic display, to stimulate the operator's senses, and (3) special-purpose hardware that links the sensors and effectors to produce sensory experiences resembling those in a physical environment. In a virtual environment, a simulation computer establishes this linkage. In the closely related technology of head-mounted teleoperation display, the linkage is accomplished by robot manipulators, vehicles, control systems, sensors, and cameras at a remote work site (Figure 1).

The display technology works by developing a real-time, interactive, personal simulation[2] of the content, geometry, and dynamics of the environment. This is directly analogous to the technology for traditional vehicle simulation.[3] But unlike vehicle simulation, virtual environment simulation is typically unmediated. The users are immersed directly in an environment, rather than placed in a vehicle simulated to be in an environment. Further, the hardware producing the simulation is more often worn than entered.

The software for a virtual environment must address three separate functions: (1) the shape and kinematics of the actors and objects, (2) their interactions among themselves and with the environment according to such rules for behavior as Newtonian laws of motion, and (3) the extent and character of the enveloping environment. A successful environmental simulation must provide adequate communications channels to address these functions.

Figure 2 presents some characteristics of the communications channels in a virtual environment system. I have compiled these values from the perceptual and motor-control literature and from consultation with researchers and developers who have practical experience regarding the human interface requirements for virtual environments. These estimates do not represent optimal, maximal, or minimal values; such values would be simulation specific, varying with specific viewing conditions— for example, whether an operator used focal or peripheral vision. Instead the values in the figure represent opinions of experienced developers and provide points of reference for future research.

Origins of the technology

We can trace much of the technology addressing these requirements directly to developments in vehicle simulation. In fact, one of the first head-mounted displays—the CAE fiber-optic helmet-mounted display—was designed to replace bulky, dome-projection flight simulators.[4] The work in vehicle simulation, however, dates from as far back as the work of Edwin Link in the late 1920s.[5] Teleoperation technology dates from the 1940s, with system components under development since the early 1960s. For example, both Philco[6] and the Argonne National Laboratory[7] worked on teleoperation displays using head-mounted, closed-circuit television systems. Figure 3 shows an early head-mounted display by Philco, and Figure 4 on page 20 shows a head-controlled TV system developed at Argonne. More recent work by Ivan Sutherland pioneered the personalized graphics simulation and the first synthetic computer-generated display used for virtual environments.[8]

Simulation hardware → Human operator (Displays); Human operator → Simulation hardware (Controls)

Transmission delay	Bandwidth	Resolution	Dynamic range	Signal/noise
Displays				
		Visual		
		Monocular		
20–100 msec	20–100Hz	2arcmin/pixel within 5° central vision	8-bit grey scale/color 60° field	25:1 contrast ratio
		Stereoscopic		
100 msec	0.1–5Hz	2arcmin/pixel within central vision	30° stereo overlap 30° field overlap 2° disparity range 0.1–6 meter-angle convergence	120:1 disparity ratio
		Haptic		
		Tactile		
5 msec	0–10kHz	10–100 micron vibration 1–2mm spatial resolution	8 bits	200:1 RMS ratio
		Kinesthetic/Force		
20 msec	50–100Hz	0.1 Newton	20N @ DC to 1N @ 10Hz 6 bits 1–10cm	64:1 RMS ratio
		Audio		
		Sound		
1 msec	20Hz–20kHz	Frequency .02–3 Hz, power 2 dB	16 bits 60 dB	40:1 RMS ratio
		Directional Sound		
50–500 msec	3–6Hz	Relative direction: 1° @ 5° C.E.P. Absolute direction: 20–30°	4π steradians	20–30:1 solid angle ratio
		Vocal (Synthetic speech)		
10–100 msec	1.5–2 words/sec	90–95% recognition in 50,000-word vocabulary	Potentially unlimited	
Controls				
		Manipulative (Mice, joysticks, pedals, trackers, etc.)		
10 msec	3–10Hz 100Hz for force reflection	0.2° joint angle 1–4 bits/dof (discrete control) 10 bits/dof (continuous control)	Range: exoskeletal limb motion 20N @ DC to 1N @ 10Hz	200:1 RMS ratio
		Vocal (Speech recognition)		
1–2 sec	1–2 words/sec	<5% probability of misrecognition	20,000 words	100:1 RMS ratio

Figure 2. System block diagram suggesting performance characteristics for the communication channels between the simulation computer and the human operator. The great variability of the characteristics emphasizes the need for significant research into the customization of virtual environments for specific purposes.

Figure 3. An early head-mounted display made by Philco engineers. The display uses virtual image viewing optics similar to contemporary head-mounted displays.

As an outgrowth of its association with interactive 3D computer graphics, virtual environment research has been pursued most intensively by aircraft simulation development groups interested in alternatives to expensive dome-projection systems and in flexible simulation of new avionics systems. The early interest of the vehicle simulation and teleoperations communities has been augmented by the work of computer scientists interested in interactive computer graphics as a human-computer interface. Most recently, interest has spread into telerobotics, scientific data visualization, planetary surface exploration, video game development, large-scale simulation networks such as SimNet, and interactive art (see Kalawsky[9] and Ellis[1,10] for general historical reviews).

NASA in particular has many application areas. Several NASA centers are pursuing research and development pro-

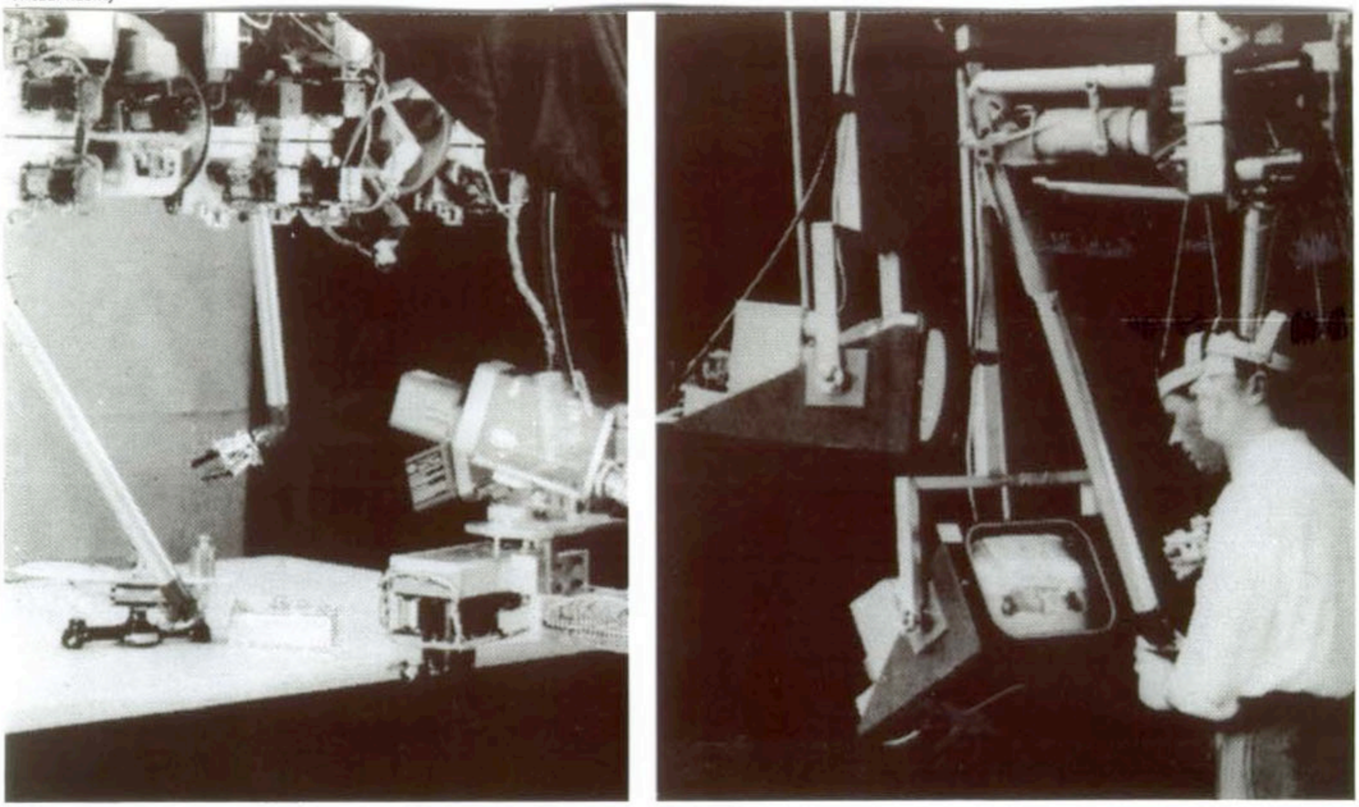

Figure 4. A multiple-exposure photograph of the experimental head-controlled television system developed at Argonne National Laboratory in the early 1960s. It used a mechanically driven boom-mounted TV display that avoided poor visual resolution by avoiding magnifying optics. A mechanical head tracker moved the display to preserve its position relative to the user.

grams developed under various program titles like applied computer graphics, scientific visualization, and telerobotics (see Figure 5).[11,12]

Commercial availability

Virtual environments have been commercially available as flight simulators for years, but achieving the performance specifications required for practical applications has been very expensive, costing tens of thousands to millions of dollars. Much cheaper high-resolution virtual environment systems have recently become commercially available. These include the Fakespace BOOM and n-Vision Datavisor, and there are now prospects for helmet displays costing only a few hundred dollars from Sega and Sony. The developers of the cheaper virtual environment systems have generally settled for much poorer performance than have systems for flight simulators. In fact, most head-mounted virtual environment display systems cannot meet basic standards for recommended scan lines per character of displayed text, such as those suggested for raster displays in aircraft cockpits.[13] Whether this strategy of marketing systems known to have poor performance will succeed remains a question. Poor performance and reliability were partially responsible for the fall of the former market leader, the now dissolved and reorganized VPL Research.

Most systems using the cheaper accessible technology have failed to pass beyond the stage of conceptual demonstration to the stage of useful work. A key element frequently missing in the research for many applications areas is a rigorous comparison of user performance with a head-mounted virtual environment display versus a well-designed panel-mounted substitute. Panel-mounted formats are publicly viewable, available with high resolution, and currently much cheaper than

Figure 5. NASA is using virtual environment displays to develop programming techniques for robots through simulation of the remote task environment. A dataglove is used to control pop-up menus and to interact with the robot as well as the computer graphics parameters of the simulation. The head-mounted display illustrated here was the second in a series of displays made for a project begun by Michael W. McGreevy at NASA Ames Research Center in 1985. This project was continued by Scott Fisher, Jim Humphries, Warren Robinett, and most recently, extended to include psychophysical and performance testing by the author.

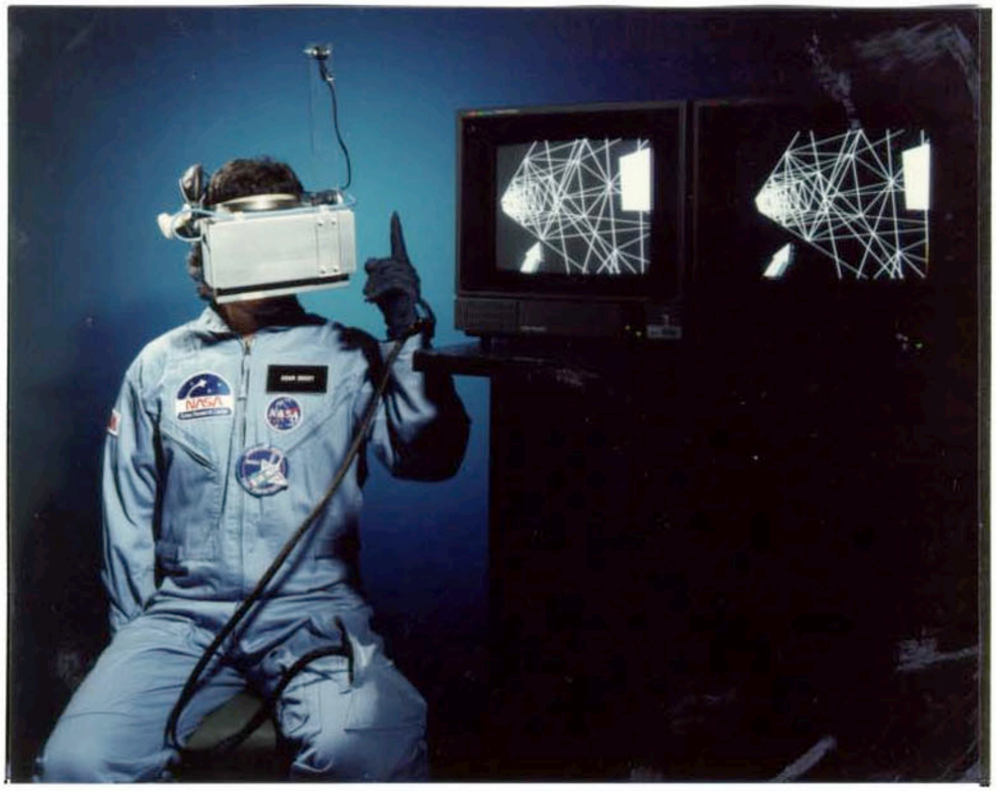

Figure 6. A virtual environment display for a personal simulation of a hand-held maneuvering device used by an astronaut who may need to fly back to a space station after accidental separation.

head-mounted virtual environment systems. Without such comparisons, the specific benefits of the new technology will remain unknown, and the market will wait on developments.

Problems and solutions

Why haven't virtual environments or the related teleoperation viewing technology generated a major commercial product outside of flight simulation in the past 30 years? The answer probably lies in the cost and performance issues relevant to the human interface, which are the key innovations of virtual environment and related display technology. Goertz's discussion about why a 1,000-line TV system can have at least 165 times poorer resolution than the human eye is strikingly contemporary, yet dates from the 1960s.[7]

The technical solutions to the many difficulties in producing a realistic personal simulation are still expensive, and many research groups investigating the technology simply don't have sufficient resources or adequate expertise for this development. Another major difficulty is that applications of the technology are sometimes fundamentally misconceived. For example, the Mattel PowerGlove, derivative of the VPL DataGlove, ultimately sold only for novelty. The PowerGlove failed to endure as a commercial product largely because its applications proved physically tiring. Unfortunately, the initial distributor for this product discouraged exploratory software development that might have solved some of the implementation problems.

The difficulty encountered by the PowerGlove project characterizes many application areas of virtual environment technology: Those advocating and sometimes even developing virtual environment displays for a particular application fail to fully understand the performance required of both the technology and the operators for successful use. For example, field use of the viewing technology can be very difficult, disorienting, and nauseogenic, as illustrated by the limited success of even well-funded attempts to use telepresence interfaces in harsh environments, such as NASA's use of head-mounted viewing devices for teleoperation in Antarctica. And the experience of the flight simulation community shows that a single application environment can require considerable human engineering expertise.

Advances in boom-mounted displays,[14] improved interfacing techniques, and six-degree-of-freedom trackers might provide a solution to the resolution problem as well as the transport delay problem. Both problems constrain practical use of virtual environment display technology. However, working virtual environment display systems in the moderate to low price range (that is, under $60,000) remain isolated to date. These displays potentially offer a compact format for personal small-vehicle training simulators, such as the hand-held maneuvering units developed for use in space (Figure 6).[15] They also provide useful alternative simulation environments for familiarizing astronauts with SpaceLab stowage requirements. But many of these applications are still essentially conceptual demonstrations needing significant further improvements in, for example, the visual resolution of head-mounted displays and the physically based modeling of interacting objects.

Nevertheless, some successful applications have appeared as the technology has matured. In Japan, Matsushita Electric Works of Osaka has used the virtual architectural walkthroughs first demonstrated by Frederick Brooks' group at the University of North Carolina.[16] These walkthroughs serve as a marketing tool to help sell custom-designed kitchens and cabinetry. W Industries (now Virtuality Entertainment Systems) has distributed "virtual reality" video games, and similar well-financed efforts are under development in the US, notably by Sega and Paramount Studios. But commercial success of specific companies working in this field remains uncertain. The uncertainty is due both to rapidly changing technical factors, like the availability of better and cheaper display technologies, and to the recent entry of large Japanese manufacturers like Sony, Olympus, and Nissan into the market. Most of the helmet manufacturers in the US are small start-ups, and VPL, once acknowledged as the industry leader, has essentially gone through bankruptcy due to overextension.

The ease with which a developer can lose focus when working in this area might be a characteristic of the technology itself.

As a communications medium, virtual environments appear to be useful for practically everything. This broad applicability in fact can be a source of difficulty.

Wanted: a virtual Visicalc

Technologies derive their strength not so much from their generality as from their uniqueness. They become truly useful when they can be customized. For example, aircraft simulators are not useful because they can simulate a generic aircraft, but because they can simulate, say, a Boeing 747SP. As flight simulation shows, however, this specificity is achieved only after considerable engineering development and human factors tuning and testing. Moving virtual environment displays from the demo room to the desktop in other application areas will require similar levels of effort. The number of economically viable applications will grow as compact, personal simulators are customized to solve specific tasks.

It must be said, however, that the virtual environment industry has not yet found its Visicalc—the "spreadsheet" application that created the microcomputer industry when thousands of potential users recognized in it a new, affordable tool that would help them do their existing jobs better and imagine solutions to previously intractable problems. Finding such an application would underscore the benefits of virtual environment displays. It is also important because the use of these displays brings risks and costs along with benefits. Like the predecessor flight simulators, virtual environments can produce nausea and altered visual and visuomotor coordination with extended use. These aftereffects can interfere with automobile driving and other aspects of normal life.

Life in virtual environments might also have social aftereffects, especially if the high level of violence in existing video games is transferred into this new medium. Consequently, the design of virtual environments might provide not only technical, but also social and possibly political challenges as well. ❑

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