

VIRTUAL REALITY

GIUSEPPE RIVA
Istituto Auxologico Italiano
Milan, Italy
and
Università Cattolica del Sacro
Cuore
Milan, Italy

1. INTRODUCTION TO VIRTUAL REALITY

Since 1989, when Jaron Lanier used the term for the first time, virtual reality (VR) has usually been described as a computer-simulated environment with and within which people can interact. The following are some examples of such definitions:

“The terms virtual worlds, virtual cockpits, and virtual workstations were used to describe specific projects. In 1989, Jaron Lanier, CEO of VPL, coined the term virtual reality to bring all of the virtual projects under a single rubric. The term therefore typically refers to three-dimensional realities implemented with stereo viewing goggles and reality gloves” [(1), p. xiii].

“I define a virtual reality experience as any in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint” [(2), p. 17].

“It is a simulation in which computer graphics is used to create a realistic-looking world. Moreover, the synthetic world is not static, but responds to the user’s input (gesture, verbal command, etc.). This defines a key feature of virtual reality, which is real-time interactivity” [(3), p. 2].

The basis for the VR idea is that a computer can synthesize a 3-D graphical environment from numerical data. Using visual, aural, haptic, and olfactory devices, the user can experience the environment as if it was a part of the real world (see Fig. 1). This computer-generated world may be either a model of a real-world object, such as a house, or an abstract world that does not exist in a real sense but is understood by humans, such as a chemical molecule or a representation of a set of data, or it might be in a completely imaginary science fiction world.

Further, because input devices sense the operator’s reactions and motions, the computer modifies the synthetic environment accordingly, creating the illusion of interacting with, and thus being immersed within, the virtual environment. The most recent development of VR has been in the area of networking and the Internet. Networked virtual environments and 3-D interfaces to the Internet are among the latest applications of VR in a growing telecommunications market.

2. VIRTUAL REALITY TECHNOLOGY

A VR system is the combination of the hardware and software that enables developers to create VR applications. The hardware components receive input from user-controlled devices and convey multisensory output to

create the illusion of a virtual world. The software component of a VR system manages the hardware that makes up the VR system. This software is not necessarily responsible for actually creating the virtual world. Instead, a separate piece of software (the VR application) creates the virtual world by making use of the VR software system.

Typically, a VR system is composed of (2,3):

- the *output tools* (visual, aural, and haptic), which immerse the user in the virtual environment;
- the *input tools* (trackers, gloves, or mice), which continually report the position and movements of the users;
- the *graphic rendering system*, which generates, at 20–30 frames per second, the virtual environment; and
- the *database construction and virtual object modeling software* for building and maintaining detailed and realistic models of the virtual world. In particular, the software handles the geometry, texture, intelligent behavior, and physical modeling of any object included in the virtual world.

According to the hardware and software included in a VR system, it is possible to distinguish between:

- *Fully Immersive VR*: With this type of solution, the user appears to be fully inserted in the computer-generated environment. This illusion is produced by providing immersive output devices (head-mounted display, force feedback robotic arms, etc.) and a system of head/body tracking to guarantee the exact correspondence and coordination of user’s movements with the feedback of the environment.
- *Desktop VR*: Desktop VR uses subjective immersion. The feeling of immersion can be improved through stereoscopic vision. Interaction with the virtual world can be made via mouse, joystick, or typical VR peripherals such as Dataglove.
- *CAVE*: Cave is a small room where a computer-generated world is projected on the walls. The projection is made on both front and side walls. This solution is particularly suitable for collective VR experience because it allows different people to share the same experience at the same time.
- *Telepresence*: Users can influence and operate in a world that is real but in a different location. The users can observe the current situation with remote cameras and achieve actions via robotic and electronic arms.
- *Augmented Reality*: The user’s view of the world is supplemented with virtual objects, usually to provide information about the real environment. For instance, in military applications, vision performance is enhanced by pictograms that anticipate the presence of other entities out of sight.



Figure 1. A cave-based VR system (courtesy of Technische Universität Berlin, Berlin, Germany).

2.1. Output Tools

2.1.1. Visual Interfaces. The visual interface provides, in many cases, the most salient and detailed information regarding the virtual world. In general, a complete visual interface consists of two primary components [(4), p. 120; (5)]:

- a visual display surface and an attendant optical system that paints a detailed, time-varying pattern of light onto the retina of the user; and
- a system for positioning the visual display surface relative to the eye of the operator.

However, the current technical limitations make both the optimal use of normal visual sensory capabilities and the real-time display of detailed, continuous-motion imagery a difficult challenge for VR developers (see Table 1 for the relevant display factors influencing human visual abilities).

In particular, the inadequate optical arrangements between the display and the user's eyes or the inadequate channel capacity in the display unit may produce spatial distortion and image degradation. For these issues, none of the many display options that currently exists is completely adequate across all applications.

Two major classes of visual display systems are available: head-mounted and off-head displays. Head-mounted displays (HMDs) are physically coupled to the head of the operator by mounting display hardware on a helmet or headband worn by the user (see Fig. 2).

The most frequently used display types for HMDs are cathode ray tubes (CRTs) and back-lighted liquid crystal displays (LCDs). In many HMDs, all the visual output is generated by computer. For certain augmented-reality displays, however, a semitransparent display surface is

used and the computer-generated visual output is overlaid on imagery resulting directly from the real environment.

A significant advantage of HMDs is that the human torso and neck provide an effective servomechanism for display positioning. Critical disadvantages of HMDs are the weight and inertial burden that interferes with the natural movement of the user, the fatigue associated with these factors, and the increased likelihood of symptomatic motion sickness with increased head inertia. Moreover, it is difficult to build HMDs that exhibit good spatial resolution, field of view, and color being lightweight, comfortable, and cost-effective. Typical low/medium-quality HMDs have a VGA or SVGA resolution ($640 \times 480/800 \times 600$ tricolor pixels), a 40/50-degree field of view, and good color saturation.

Off-head displays, including desktop monitors and projection technologies such as panoramic displays, Caves, and workbenches, come off the user's head and surround the user with virtual scenery.

Caves are VR installations, first introduced at the University of Illinois-Chicago, based on surround-projection technology (see Fig. 3).

From three to six faces of a rectangular solid are fitted with rear-projection screens, each driven by one of a set of coordinated image-generation systems. Typically, computer-generated stereoscopic images are projected onto the faces and viewed through shutter glasses to generate the 3-D effect.

The principal advantages of surround-projection displays are a wide, surrounding field of view, and the ability to give a shared VR experience to a small group. The principal disadvantages are the cost of multiple image-generation systems, the space requirements for rear projection, and the brightness and contrast limitations because of large screen size and light scattering.

Table 1. Display Features Influencing Human Visual Abilities (5)

Visual Abilities	Display Factors			
	More relevant		Less relevant	
Stereopsis	Interlace Frames	Frame Disparity	Monocular Monitors	
Spatial Vision	Pixel Size and Spacing	Pixel Number	Screen Size	Gray Scale
Color Vision	Phosphor Types	Phosphor Number	Bit Depth	Gun independence and stability
Image Motion	Phosphor Decay	Raster Rate	Pixel Size and Spacing	
Observer Motion	Scene Update	Field of View		

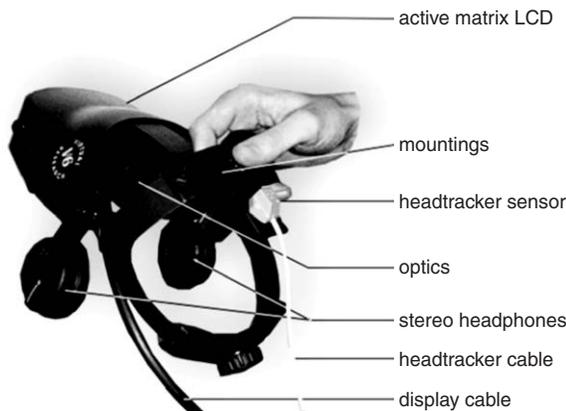


Figure 2. The components of a head-mounted display (courtesy of Institut Für Anwendungsorientierte Wissensverarbeitung, University of Linz, Linz, Austria).

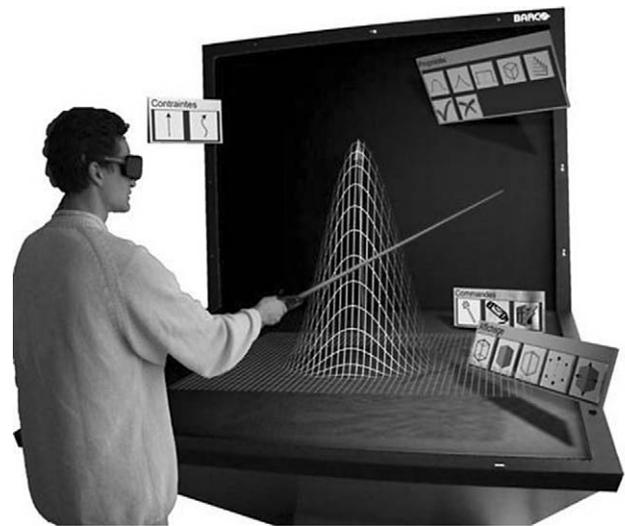


Figure 4. A VR workbench (courtesy of the Image Sciences, Computer Sciences and Remote Sensing Laboratory, Louis Pasteur University, Strasbourg, France).

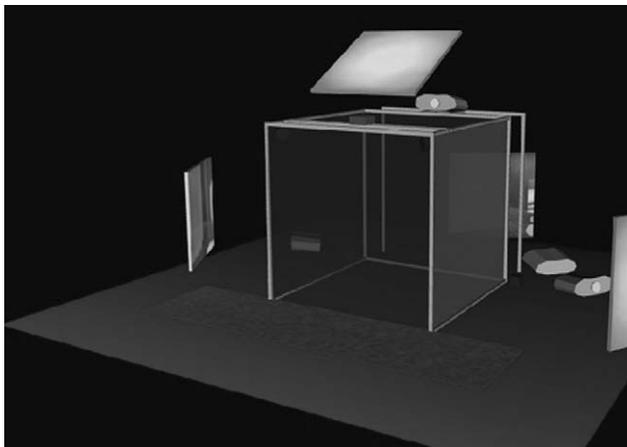


Figure 3. The structure of a Cave-based VR system (courtesy of the Electronic Visualization Laboratory, University of Illinois-Chicago, Chicago, IL).

A VR workbench allows the visualization and interaction with computer-generated scenes in a tabletop environment (see Fig. 4). The workbench configuration lays a rear-projection screen flat and positions the projector so that the workbench’s length approximates that of a human body. Right and left eye images are projected onto a mirror so that users wearing stereoscopic shutter glasses can observe a 3-D image above the tabletop. Group

members can observe the 3-D scene as manipulated (via tracked glove or laser pointer) by the group leader.

The main advantage of workbenches is that two or more tracked viewers may perceive simultaneously a custom-generated image while viewing the virtual world. This paradigm is an excellent match for many real-world tasks. For example, a doctor performing a virtual surgery probably does not want to be completely immersed in a virtual operating room surrounded by virtual assistants and virtual equipment. On the other side, the cost of workbenches is high, the sense of immersion is low, and they have some brightness and contrast limitations.

2.1.2. Aural Interfaces. Auditory cues increase awareness of surroundings, cue visual attention, and convey a variety of complex information without taxing the visual system. However, auditory processing is often given minimal attention when designing virtual environments. A possible explanation is the complexity of auditory perception (see Table 2 for a summary of the main properties of sound): It is affected by physiology, expectation, and even the visual interface (6).

In general, aural interfaces convey basic information about the virtual environment to the user. Between these

Table 2. The Main Properties of Sound (6)

Sound	Sound is a pressure wave produced when an object vibrates rapidly back and forth.
Sound production	The diaphragm of a speaker produces sound by pushing against molecules of air, thus creating an area of high pressure (condensation). As the speaker diaphragm returns to its resting position, it creates an area of low pressure (rarefaction).
Wavelength	A complete condensation and rarefaction (the point where the wave repeats itself) constitutes the wavelength of the wave.
Frequency	The frequency of the sound stimulus is determined by the ratio between the velocity at which the wave is traveling and its wavelength.
Intensity	The intensity of the sound stimulus is determined by the amplitude of the waveform. Intensity is measured in decibels (dB).

data, one of the most important is *localization*, the location of a sound source.

Functionally, aural localization is distinctly different from that of vision and proprioception. For the other spatial senses, position is neurally encoded at the most peripheral part of the sensory system. In contrast, the spatial information embedded in the auditory signals reaching the left and right ears of a listener is computed from the peripheral neural representations.

For this reason, the most robust cues for source position depend on differences between the signals reaching the left and right ears. The direction of a source is determined primarily by comparing the signals received at the two ears to evaluate the interaural amplitude ratio and the interaural time delay as a function of frequency. Such *interaural* or *binaural* cues are robust specifically because they can be computed by comparing the signals reaching each ear. As a result, binaural cues allow the listener to factor out those acoustic attributes that develop from source *content* from those attributes that develop from source *position*.

Instead, the perception of sound source distance is generally poorer (4). This ability is based on the following

three changes in the received signal, as source distance is increased: a decrease in intensity, an increase in high-frequency attenuation, and an increase in the ratio of reflected to direct energy. The difficulty in evaluating sound source distance is related to their lack of reliability: They all can be influenced by factors other than distance.

Spatial auditory cues can be simulated using headphone displays or loudspeakers (6). Headphones generally allow more precise control of the spatial cues presented to the listener: On one side, the signals reaching the two ears can be controlled independently; on the other side, there is no indirect sound reaching the listeners (i.e., no echoes or reverberation). However, professional headphones are generally more expensive than loudspeaker displays and may be impractical for applications in which the user does not want to wear a device on the head. Although it is more difficult to control the spatial information reaching the listener in a loudspeaker simulation, loudspeaker-based simulations are relatively simple and inexpensive to implement and do not interfere with the user. In general, the ability to generate an accurate spatial simulation using loudspeakers increases dramatically as the number of speakers used in the display increases (see Table 3 for the most common multi-loudspeakers configurations).

2.1.3. Haptic Interfaces. Being able to touch, feel, and manipulate objects in an environment, in addition to seeing (and hearing) them, provides a sense of immersion in the environment that is otherwise not possible.

For this reason, haptic interfaces are devices that enable manual interaction—eventually including tactile feedbacks—with a virtual environment (7). In performing tasks with a haptic interface, the user produces desired motor actions by physically manipulating the interface, which, in turn, displays tactual sensory information to the user by stimulating the tactile and kinesthetic sensory systems (8).

In general, the interface receives motor action commands from the human user and displays appropriate tactile feedbacks to him/her (see Fig. 5 for an advanced haptic interface). This feedback is achieved by applying a degree of opposing force to the user along the x, y, and z axes. In fact, by using haptic interfaces, the user can not only feed information to the virtual environment but can receive information from it in the form of a felt sensation on some part of the body: Unlike vision and audition that

Table 3. The Surround Sound Systems

Number of speakers	Name of the System	Configuration of the System
5.1	Dolby Digital Surround	Speakers are located at the left, middle, and right in front of the listener, and left and right behind the listener. The so-called 0.1 speaker is a subwoofer.
5.1	Digital Theater Systems (DTS)	As above.
6.1	Dolby Digital Surround EX	As the typical 5.1 configuration plus a center speaker behind the listener.
7.1	Sony Dynamic Digital Sound® (SDDS®)	As the typical 5.1 configuration plus a left center and right center speaker in front of the listener

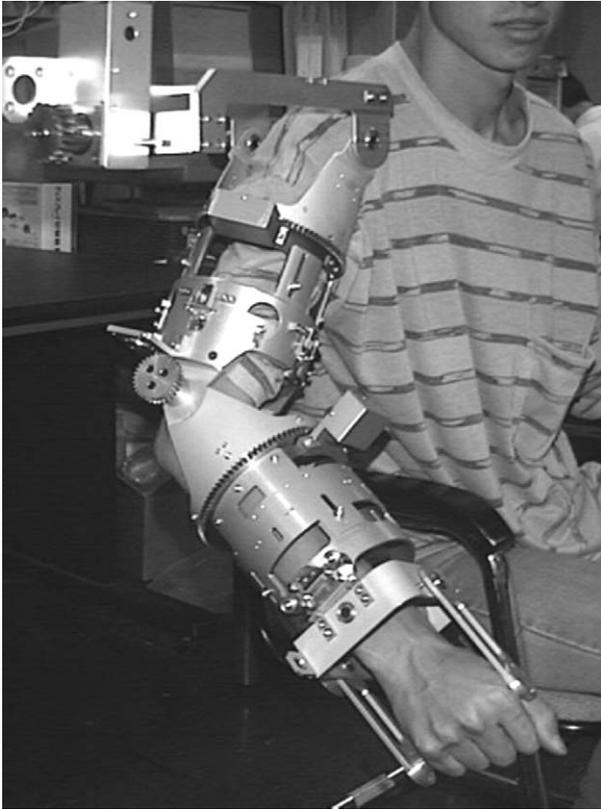


Figure 5. Sensor arm, an exoskeleton-type haptic device (courtesy of the Hashimoto Lab., IIS, The University of Tokyo, Tokyo, Japan).

are mainly input systems for the human observer, the haptic system is bidirectional.

Thus, in general, haptic interfaces can be viewed as having two basic functions. First, they measure the positions and contact forces (and time derivatives) of the user's body parts. Second, they display contact forces and positions (or their spatial and temporal distributions) to the user.

Joysticks, mice, and trackballs constitute relatively simple interfaces providing haptic feedback. The simplest forms are "rumble packs," which are simply attachments, that vibrate on command from the software. Some also support force feedback. For instance, simulated automobile steering wheels are now available that provide the road "feel" for race car simulations. Other examples of haptic interfaces available in the market are gloves and exoskeletons that track hand postures.

Advanced haptic interfaces usually have two components: *tactile* (or cutaneous) sensing, and *kinesthetic* sensing, (or proprioception). Kinesthetic sensing refers to an awareness of limb position and movement as well as muscle tension. Tactile sensing refers to an awareness of stimulation to the outer surface of the body (9).

Haptic interfaces are usually employed for tasks that are usually performed using hands in the real world, such as manual exploration, surgical training, and manipulation of objects.

2.1.4. Olfactory Interfaces. Virtual olfactory interfaces, adding the smells of the world to the VR experience, are one of the least developed areas within the field of human-computer interaction. However, with the advent of VR technology, olfactory interfaces are now seen as a valuable sensory cue for applications such as emergency or surgical training (10): Olfactory interfaces may increase the sense of presence in the virtual environment immersion with a flood of vibrant fragrances.

The virtual olfactory interfaces that produce odors, related to target odors, in a controlled way are usually defined *virtual olfactory display* (VOD) (11).

Virtual olfaction is instead defined as the act of smelling an odorant produced by a virtual olfactory display. The last concept is *teleolfaction*, defined as the act of smelling a mixture of odorants whose composition is related to a mixture present in a remote place.

Odorant storage is, perhaps, the most mature of the various technologies required for a virtual olfactory display (12). Odorants can be stored in a number of ways, including liquids, gels, or waxy solids. The most popular storage method for previous and current VE-related work seems to be to microencapsulate odorants: droplets of liquid are encapsulated in a wall of gelatin and printed on a flat surface using silk screen techniques. This method is the basis of scratch-and-sniff patches, where the odorant is released by subjecting the particle to mechanical shear or melting the gelatin wall. Microencapsulation offers the advantages of discrete metering of odorant dosage, stability at room temperatures, and the unlikelihood of messy spills. Other commonly used methods include air dilution olfactometry, breathable membranes coated with a liquid odor, and a system of liquid injection into an electrostatic field with air flow control (12).

Olfactory delivery systems for VEs, however, require more than odor storage and display (10). A first critical area now under investigation is position tracking: For a person moving through a virtual world and smelling objects as he/she approaches them, the integration of the smell technologies and the user's position is essential. A second research area concentration is duration regulation: The researchers are trying to ensure that the strength of the smell is proper and that the smell persists only as long as it would in the natural environment.

2.2. Input Tools

Even if it is possible to interact with a virtual environment using simple tools, such as a joystick, a keyboard, or a mouse, the most important input devices in a virtual reality system are position trackers, the device (or system of devices) that reports the position and orientation of the user to the host computer that creates the virtual environment.

Tracker technologies are characterized by the number of targets tracked, resolution, accuracy, latency, the spatial volume, environmental constraints, and the technology used (see Table 4 for the main criteria for evaluating tracker performances). Generally, tracking multiple targets requires more processing: Head and pointer tracking require only two targets, whereas avatar and multiuser

Table 4. The Criteria for Evaluating Tracker Performances

Criteria	Definition
Resolution	The smallest change in position and orientation that can be detected by the tracker.
Accuracy	A measure of the error in the position and orientation reported by the tracker.
Latency	The delay between a change in position and orientation and the report of the change to the host computer.
Spatial volume	The space in which the tracker can effectively measure position and orientation.
Update rate	The rate at which position and orientation measurements are reported by the tracker to the host computer.

systems require many different targets. Typically, body tracking is for locomotion and visual displays, hand and arm tracking is for haptic interfaces, and head and eye tracking is for visual displays.

The main tracking technologies used are: magnetic, acoustic, inertial, optical, and mechanical.

2.2.1. Magnetic Trackers. Magnetic trackers contain a source transmitter and a receiver (13): The transmitter pulses magnetic fields in various orientations and the receiver determines the strength and angles of the fields.

The sensors of magnetic trackers are small and light in weight. Hence, they can be worn comfortably by the users and moved between body parts without problems. Further, magnetic trackers do not have any line-of-sight problems. They can track even if an obstruction exists between the transmitter and the receiver, provided that the obstruction is not metallic or ferromagnetic.

The main disadvantage of magnetic trackers is that of distortion: Pulsing magnetic fields induce magnetic fields in metallic objects in the environment producing distortions and errors in the tracking results. In addition, these trackers are adversely influenced by distortions caused by external electromagnetic fields, e.g., those from CRT displays.

2.2.2. Acoustic Trackers. Acoustic trackers use microphones to get time-of-flight measurements from ultrasonic sound sources. The approaches used are (13):

- measuring the time taken by ultrasonic pulses to travel from a set of transmitters to a set of receivers; and
- comparing the phases of emitted acoustic waves with the phase of a reference wave.

Both kinds of acoustic trackers are small and light in weight and, unlike magnetic trackers, do not suffer from distortions in the presence of magnetic fields. However, they are unable to function correctly if obstructions exist between the transmitters and the receivers, and are

susceptible to interference from environmental noise and echoes.

2.2.3. Inertial Trackers. Inertial trackers use passive magnetometers, accelerometers, and gyroscopes to compute the relative change in position and orientation from the appearing acceleration and angular velocity in the moving target with respect to an inertial reference coordinate system (generally the earth's magnetic field) (14). Typically, the inertial tracker senses gravity to establish which direction is down and integrates a two-axis rate gyroscopic measurement to provide yaw.

Inertial trackers are usually cheaper than magnetic and acoustic trackers and do not have range limitation or line-of-sight restrictions. They are, however, subject to accumulation of errors resulting in drift.

2.2.4. Optical Trackers. Optical trackers rely on vision algorithms to extract the location of targets from images captured by video cameras (15). Most optical trackers are beacon trackers, they track either active (i.e., transmitters of light) or passive (i.e., reflectors of light) beacons using cameras or photo-diode sensors.

Depending on the position of the beacons and the sensors, beacon trackers can be divided into two categories: the inside-out and the outside-in systems. Inside-out systems place the beacons at fixed places in the environment and the sensors on the target object. On the other hand, outside-in systems place the beacons on the target object and the sensors at fixed places in the environment.

Optical trackers have high update rates, provide low latency, and are scalable to fairly large areas. On the other hand, all optical trackers suffer from line-of-sight problems. The problem can be partly mitigated by using multiple sensors and beacons. Moreover, the performance of optical trackers is adversely affected by ambient light and infrared radiation. So the surrounding environment has to be designed carefully to reduce ambient radiation. Finally, inside-out optical trackers require elaborately designed environments. Hence, they are not very portable and are expensive.

2.2.5. Mechanical Trackers. Mechanical trackers can be a relatively accurate means of tracking head or body-segment positions (3): They connect a known point to the tracked object through a set of jointed linkages whose motion is measured. Mechanical trackers can measure up to full body motion and do not have intrinsic latencies. Two types are distinguished, depending on whether the mechanical linkages are entirely worn (body-based, such as goniometers and esoskeletons), or are partly attached to the ground (ground-based). Ground-based linkages are easier to actuate for force reflection than are body-based linkages, because actuators do not have to be placed and carried on the body. The main advantages of these trackers are the low latency and the high level of accuracy. However, even if they are fairly easy to build, they are cumbersome and less common than the other trackers.

2.3. The Generation of Virtual Environments

The computer technology that allows the development of 3-D virtual environments consists of both hardware and software (4). The computer hardware used ranges from standard PCs to high-performance workstations with parallel processors and specialized graphic cards for the rapid computation of world models, and high-speed computer networks for transferring information among participants in the virtual world. The implementation of the virtual world is accomplished with software for modeling (geometric, physical, and behavioral), navigation, interaction, and hypermedia integration.

2.3.1. 3-D Graphics. The availability of computer graphics workstations capable of real-time, 3-D display at high frame rates is probably the key development behind the current push for realistic virtual environment. In fact, the generation and displaying of 3-D objects in a 2-D space is a complex process requiring considerable memory and processing power.

The main difference between 2-D and 3-D computer graphics is the use of 3-D representation of geometric data (16). In a 2-D graphic scene, each pixel (short for “PIcture ELement”, a single point in a graphic image) has the following properties: position, color, and brightness. When 3-D graphics are considered, each pixel requires a new property, depth, that indicates where the point lies on an imaginary z-axis.

The process of adding depth to an image using a set of cross-sectional images—known as a volumetric dataset—is defined *voxelization* (from *voxel*: VOLUME piXEL). When many 3-D pixels are combined, each with its own depth value, the result is a 3-D surface, called a texture. Once a texture has been defined, it can be wrapped around any 3-D object.

In this context, a key role is played by rendering: the process of adding realism to a computer graphics by adding 3-D qualities such as shadows and variations in color and shade (see Table 5 for the most common rendering techniques). Rendering in virtual reality is calculated and displayed in real time, at rates of approximately 20 to

120 frames per second. Animations for noninteractive media, such as video and film, are rendered much more slowly.

In the past, 3-D graphics were available only on powerful workstations, but now 3-D graphics accelerator are commonly found in personal computers. To handle the computational operations required by the rendering process, a graphics accelerator contains its own memory and a specialized microprocessor.

2.3.2. VR Development Environments. A VR development environment provides developers with the software framework, libraries, and run-time needed to develop and execute VR applications (17). It abstracts hardware and software complexities in the system, thereby allowing users to write applications without having to know every detail of the system.

Typical VR development tools include four main components that act in consort and in real time to create a virtual world (4):

- World modeling: It defines the form, behavior, and appearance of objects included in the virtual environment, which is achieved by including all the geometric, surface, and physical properties needed for physical simulation and rendering purposes.
- Visual scene navigation software: It provides the means for moving the user through the virtual environment.
- Interaction software: On one side, it provides the mechanism to construct a dialogue from various control devices (e.g., trackers, haptic interfaces). On the other side, it applies that dialogue to a system or application, so that the multimodal display changes appropriately.
- Hypermedia integration software: it allows hypernavigation, which involves the use of nodes that can be traveled within.

Most VR software environments are tied to specific technologies or to particular requirements of individual applications. For instance, some systems make use of hardware-specific features, thus tying the users to specific hardware architectures. Other systems restrict developers to only using a limited set of software tools in their applications. Although this approach was effective when VR systems were built as proofs of concept, it is now limiting the growth of VR applications.

There have been some attempts at creating standards, even open-source ones, but most of them either focus on specific uses and requirements or are monolithic packages that offer little flexibility to developers (17).

Table 5. Rendering Processes

Scanline rendering	It is a rendering algorithm that works on a point-by-point basis: some point in a line is calculated, followed by successive points in the line. When the line is finished, rendering proceeds to the next line.
Ray tracing	It works by tracing the path taken by a ray of light through the scene, and calculating reflection, refraction, or absorption of the ray whenever it intersects an object in the world.
Radiosity	Unlike ray tracing, which tends to simulate light reflecting only once off each surface, it simulates the many reflections of light around a scene, generally resulting in softer, more natural shadows and reflections.

3. VIRTUAL REALITY EXPERIENCE

As we have just seen, VR is usually described as a particular collection of technological hardware. However, it is possible to describe virtual reality in terms of human experience, rather than technological hardware, using the

concept of *presence* (18,19): VR is the medium able to induce the experience of “presence” in a computer-generated world.

Presence is usually defined as the “sense of being there” (19), or the “feeling of being in a world that exists outside the self” (20,21).

3.1. A Definition of Presence

Lombard and Ditton (22) describe presence as the “perceptual illusion of non-mediation,” a level of experience where the technology and the external physical environment disappear from the user’s phenomenal awareness. The term *perceptual* shows that the illusion involves continuous (real time) responses of the human sensory, cognitive, and affective processing systems to objects and entities in a person’s environment. And, what’s more, a subject experiences an *illusion of non-mediation* when he or she fails to perceive or acknowledge the existence of a medium in his/her communication environment and responds as he/she would if the medium was not there.

Consensus exists that the experience of presence is a complex, multidimensional perception (see Fig. 6), formed through an interplay of raw (multi-) sensory data and various cognitive processes (23).

Two general categories of variables can determine a user’s presence: media characteristics and user characteristics. Characteristics of the medium can be subdivided into media form and media content variables. Both of these variables are known to have a significant impact on the individual’s sense of presence such that, depending on the levels of appropriate, rich, consistent, and captivating sensory stimulation, varying levels of presence can be produced.

Recently, different VR researchers have conceptualized presence more broadly to address the question of why people feel a sense of presence in any setting, computer generated or otherwise (20,24–31).

According to this approach, individuals may feel a greater degree of presence in different situations depending on the degree of meaning and agency experienced in it. Thus, an inhabitant of the Amazon rainforest, rich in ethnobotanical knowledge, may feel a fuller sense of presence while walking through the forest than an urban visitor admiring the beauty. Similarly, a computer-literate person may feel a greater sense of presence while surfing the Web than a computer novice.

3.2. The Cognitive Processes Behind Presence

Recent research suggests that, on the process side, presence may be divided in three different cognitive layers/subprocesses (21), described in Fig. 7, phylogenetically different, and strictly related to the evolution of self (32):

- *proto presence* (self vs. non-self);
- *core presence* (self vs. present external world);
- and *extended presence* (self relative to present external world).

More precisely, *proto presence* can be defined as the process of internal/external separation *related to the level of perception-action coupling (self vs. non-self)*. Proto presence is based on proprioception and other ways of knowing bodily orientation in the world. In a virtual world, it is sometimes known as “spatial presence” and requires the tracking of body parts and appropriate updating of displays.

Core presence can be described as *the activity of selective attention made by the self on perceptions (self vs. present external world)*. Core presence is based largely on vividness of perceptible displays, which is equivalent to “sensory presence” (e.g., in nonimmersive VR) and requires good quality, preferably stereographic, graphics, and other displays.

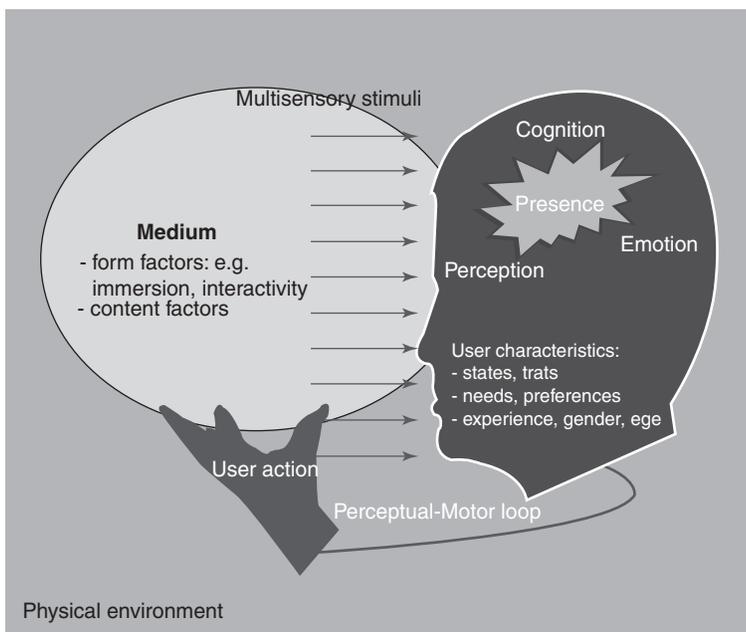


Figure 6. A general framework of presence reprinted with permission from IJsselstein & Riva (23).

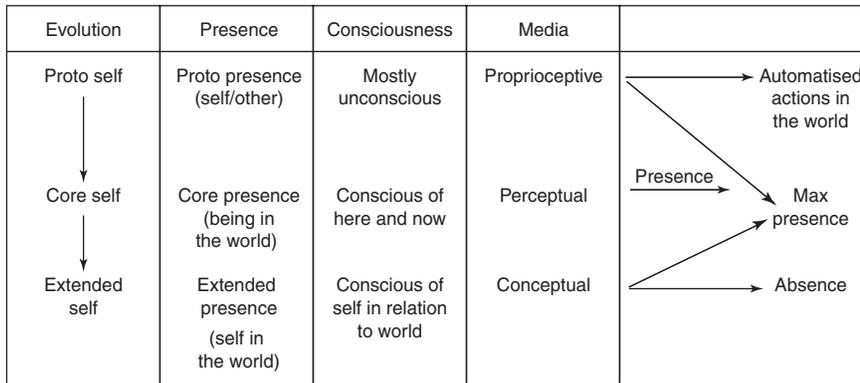


Figure 7. The layers of presence reprinted with permission from Riva et al. (21).

The role of extended presence is to verify the significance to the self of experienced events in the external world (self relative to the present external world). Extended presence requires intellectually or emotionally significant content. So, reality judgment influences the level of extended presence—a real event is more relevant than a fictitious one—and then the level of presence-as-feeling.

3.3. Presence and Quality of Experience

If presence, on the process side, can be divided in three different subprocesses, the sense of presence is a unitary feeling related to the quality of the experience of the subject. It corresponds to what Heidegger (33) defined “the interrupted moment of our habitual standard, comfortable *being-in-the-world*.” Subjectively, a higher level of presence is experienced by the self as a better quality of action and experience (31,34). On the other side, Winograd and Flores (35) refer to presence disruptions as *break-downs*: A *breakdown* occurs when, during our activity, an aspect of our environment that is usually taken for granted becomes part of our consciousness. If this event happens, attention is shifted from action to the object or environment to cope with it.

To illustrate, imagine sitting outdoors engrossed in reading a book on a pleasant evening. As the sun sets and the light diminishes, one continues reading, engrossed in the story until one becomes aware that the light is no longer suitable for reading. In such conditions, before any overt change in behavior, what is experienced is a breakdown in reading and a shift of attention from the book to the light illuminating the book.

This vision suggests that an effective VR experience is able to avoid breakdowns and to effectively support agency and meaning. In particular, maximal presence occurs when proto consciousness, core consciousness, and extended consciousness are focused on the same external situation or activity (21). As underlined by Damasio (32), proto consciousness deals mostly with bodily orientation in the world; in a VR, the proto-presence layer is mostly addressed through body tracking and sensorimotor coupling. Core consciousness deals with the perceptual world of the here and now (32); in a VR, the core-presence layer is addressed mostly through the vividness of the various displays. Finally, in a VR, the extended-presence layer is

addressed through the content. When the other layers are integrated with core consciousness, intense presence is experienced. But when they are not integrated, presence is less strong (“unfocused”), which will happen if, for example, the body tracking (proto layer) has significant deficiencies, such as lag, or if the semantic content (extended layer) directs attention away from the display toward the internal world of the imagination.

Following this approach, Zahoric and Jenison (31) underline that “*presence is tantamount to successfully supported action in the environment*.” In fact, this vision shifts the attention of the developers from the quality and realism of the virtual world to the affordances offered by it and the actions needed to exploit them. A key role is also played by the social distribution of knowledge and action, the cultural grid providing the common reference ground for joint activity, and the rules governing it.

4. APPLICATIONS OF VIRTUAL REALITY IN MEDICINE

For many health-care professionals, VR is first of all a technology. However, the analysis of the different VR applications clearly shows that the focus on technological devices is not the same in all the areas of medicine and it is related to the specific goals of the health-care provider.

For instance, Rubino et al. (36), McCloy and Stone (37), and Székely and Satava (38) in their reviews describe VR as “a collection of technologies that allow people to interact efficiently with 3-D computerized databases in real time using their natural senses and skills” (37). This definition lacks any reference to head-mounted displays and instrumented clothing such as gloves or suits. In fact, less than 20% of VR health-care applications in medicine are actually using any immersive equipment.

However, if our attention is shifted to behavioral sciences and rehabilitation, where immersive devices are used by more than 50% of the applications, VR is described as “an advanced form of human–computer interface that allows the user to interact with and become immersed in a computer-generated environment in a naturalistic fashion” (39).

These two definitions underline two different applicative focuses in medicine: VR as simulation tool and VR as interaction tool.

For physicians and surgeons, the simulation focus prevails on the interaction one: Their ultimate goal of VR is the presentation of virtual objects to all of the human senses in a way identical to their natural counterpart (38). As noted by Satava and Jones (40), as more and more of the medical technologies become information-based, it will be possible to represent a patient with higher fidelity to a point that the image may become a surrogate for the patient—the *medical avatar*. In this sense, an effective VR system should offer real-like body parts or avatars that interact with external devices such as surgical instruments as near as possible to their real models.

For clinical psychologists and rehabilitation specialists, the interaction focus prevails on the simulation one: They use VR to provide a new human-computer interaction paradigm in which users are no longer simply external observers of images on a computer screen but are active participants within a computer-generated 3-D virtual world (41,42). Within the VE, the patient has the possibility of learning to manage a problematic situation related to his/her disturbance. The key characteristics of virtual environments for these professionals are both the high level of control of the interaction with the tool without the constraints usually found in computer systems and the enriched experience provided to the patient (39).

In the following paragraphs, these two visions will be discussed in more detail, describing more in detail six areas of medicine in which the use of VR is actually investigated.

4.1. VR as Simulation Technology

4.1.1. Surgical Simulation and Planning. Surgeons know well that in training no alternative exists to hands-on practice. However, students wishing to learn laparoscopic procedures face a tough path (4): Usually they start using laparoscopic cholecystectomy trainers consisting of a black box in which endoscopic instruments are passed through rubber gaskets. After, the students begin practicing these techniques on inanimate tissues, when allowed by their cost and availability. Obviously, a substantial difference exists for students between training with artificial or inanimate tissues and supervised procedures on real patients, which is why in early 1990s different research teams tried to develop VE simulators (43,44). The science of virtual reality provides an entirely new opportunity in the area of simulation of surgical skills using computers for training, evaluation, and eventually certification (45). However, the first simulators were limited by low-resolution graphics, the lack of tactile input and force feedback, and the lack of realistic deformation of organs. In the last years, a new generation of simulator has appeared that has showed improved training efficacy over traditional methods (46–48). For instance, a randomized trial using the minimally invasive surgery training-virtual reality (MIST-VR) trainer (49,50) showed that virtual reality simulation was effective in training the novice to perform basic laparoscopic skills (see Fig. 8).

Further, the increased pressure to reduce the use of animals in technical training has led to use VR in teaching microsurgery (51). This new technology may prove to be a

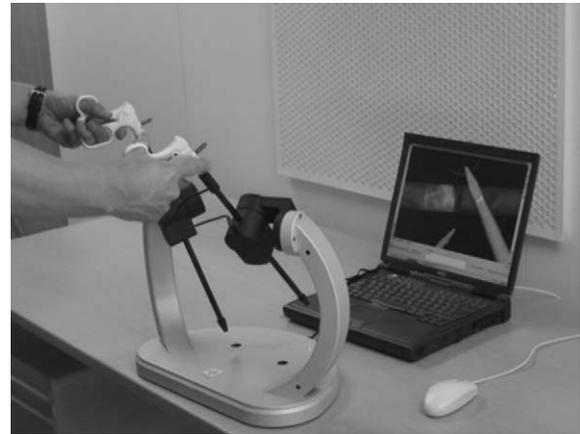


Figure 8. The minimally invasive surgery training-virtual reality, MIST-VR (courtesy of Virtual Presence Ltd., London, United Kingdom).

cost-effective, portable, and nonhazardous way forward in microsurgical training.

Another typical use of visualization applications is the planning of surgical and neurosurgical procedures (52–54). The planning of these procedures usually relies on the studies of series of 2-D MR (Magnetic Resonance) or CT (Computer Tomography) images, which have to be mentally integrated by surgeons into a 3-D concept. This mental transformation is difficult, because complex anatomy is represented in different scanning modalities, on separate image series, usually found in different sites/departments. A VR-based system is capable of incorporating different scanning modalities coming from different sites providing a simple-to-use interactive 3-D view. However, even the most advanced surgical simulators have still some limitations in creating realistic 3-D objects with deformable behavior (55). Deformable models have two conflicting characteristics: interactivity and motion realism. Nevertheless, the different surgical simulations developed to date have promoted only one of these (usually interactivity) to the detriment of the other (biomechanical realism).

In summary, an emerging body of evidence exists to establish the validity of VR surgical simulations (56). Nevertheless, refinement of simulation techniques, identification of specific performance measures, longitudinal evaluations and comparison with practice outcomes are still needed to establish the validity and the value of surgical simulation for teaching and assessing surgical skills prior to considering implementation for certification purposes.

4.1.2. Telepresence Surgery. In telepresence surgery, the VR system acts as the hands and eyes of a surgeon operating from a considerable distance (57), which enables the surgeon to offer a variety of surgical services through gaining true telepresence by the interface of the telecommunication link and a surgical robotic system. Currently, robotic-assisted telepresence surgical systems are used for the removal of the prostate, pediatric, gynecologic, thor-

acic, orthopedic, neurosurgery, and gastrointestinal cancers (57).

Although drawbacks and limitations exist for the use of surgical robotics, the systems are developing rapidly and an expanded role for this technology in the future of surgery is possible (58). The limited use of robot-assisted remote telepresence surgery to date has demonstrated that it is technologically feasible and safe, but also that the patients are willing to accept its limitations when it is used in an environment where significant value from its use is realized. Nonetheless, these technologies are still in an early stage of development, and each device entails its own set of challenges and limitations for actual use in clinical settings (59).

Another emerging area of telepresence surgery is tele-surgical mentoring (60): An experienced surgeon assists or directs another less experienced surgeon who is operating at a distance. 2-D and 3-D, video-based laparoscopic procedures are an ideal platform for real-time transmission and thus for applying telementoring to surgery. The goal of telesurgical mentoring is to improve surgical education and training by allowing access to surgical specialists in underserved areas.

4.1.3. Virtual Endoscopy. Endoscopy allows a real-time exploration of the inner surfaces of hollow organs using optical, video-assisted technology. By changing the position of the endoscope, the operator can view the inside of an organ while controlling the viewing position and angle of the probe.

Even if endoscopy has a critical role as an assessment tool, it is not perfect:

- all endoscopic procedures are invasive;
- the patients are subject to complications such as perforation, bleeding, and so on; and
- endoscopes display only the inner surface of hollow organs and yield no information about the anatomy within or beyond the wall.

To overcome these problems, different researchers are investigating the possibility of virtual endoscopy (36,61). Virtual endoscopy is a new procedure that fuses computed tomography with advanced techniques for rendering 3-D images (see Fig. 9) to produce views of the organ similar to those obtained during “real” endoscopy (62).

Ordinarily, the examination of a patient pathology would require threading a camera inside his body. This new method skips the camera and can give views of regions of the body difficult or impossible to reach physically (e.g., brain vessels).

A virtual endoscopy is performed by using a standard CT scan or MRI scan (40), reconstructing the organ of interest into a 3-D model, and then performing a fly through it. Two basic methods exist that can be used to obtain an artificial surface from the scans: *surface rendering*, in which a wireframe model consisting of small triangles is reconstructed, or *volume rendering*, that displays the entire range of voxels within a volume. Even if volume rendering is the actual standard, both approaches

allow the modification of the viewing angle, light source, depth encoding, shading effects, and surface characteristics in the reconstructed images. Typical examples include the colon, stomach, esophagus, tracheo-bronchial tree (bronchoscopy), sinus bladder, ureter and kidneys (cystoscopy), pancreas, or biliary tree (63).

Virtual endoscopy is completely noninvasive and thus without known complications (64). Other practical benefits include better patient tolerance, reduced risk, no requirement for sedation, and rapid examination times. However, important issues remain unsettled in many areas, including data acquisition, image rendering and spatial resolution, and diagnostic interpretation limiting its use (65).

In conclusion, any virtual endoscopy system must meet requirements of efficiency, effectiveness, and sensitivity. Potentially, virtual endoscopic methods, which combine the features of endoscopic viewing and cross-sectional volumetric imaging, may provide an advance in diagnosis. Nevertheless, the cost-effectiveness of virtual endoscopy remains an open question, and the diagnostic efficacy of this technology is still under study (66).

4.1.4. Medical Education. The teaching of anatomy is mainly illustrative, and the application of VR to such teaching has great potential (67,68). Through 3-D visualization of massive volumes of information and databases, clinicians and students can understand important physiological principles or basic anatomy (69). For instance, VR can be used to explore the organs by “flying” around, behind, or even inside them. In this sense, VEs can be used both as didactic and experiential educational tools, allowing a deeper understanding of the interrelationship of anatomical structures that cannot be achieved by any other means, including cadaveric dissection.

A significant step toward the creation of VR anatomy textbooks was the acquisition of the visible human male and female data made in August of 1991 by the University of Colorado School of Medicine (70). The visible human female dataset contains 5189 digital anatomical images obtained at 0.33 mm intervals (39 Gbyte). The male dataset contains 1971 digital axial anatomical images obtained at 1.0 mm intervals (15 Gbyte) (71). Actually, the U.S. National Library of Medicine in partnership with other US government research agencies has begun the development of a tool kit of computational programs capable of automatically performing many of the basic data handling functions required for using visible human data in applications (72).

The National Library of Medicine made the datasets available under a no-cost license agreement over the Internet, which allowed the creation of a huge number of educational VEs. In their recently edited book, Westwood and colleagues (73) report more than ten different educational and visualization applications.

In the future, the development of different VR dynamic models illustrating how various organs and systems move during normal or diseased states, or how they respond to various externally applied forces (e.g., the touch of a scalpel) can be expected.



Figure 9. A virtual endoscopy system (courtesy of the Surgical Planning Laboratory, Brigham and Women's Hospital, Boston, MA).

4.2. VR as Interaction Technology

4.2.1. VR in Clinical Psychology. VR is starting to play an important role in clinical psychology (74,75), that is expected to increase in the next years (76,77).

In most VEs for clinical psychology, VR is used to simulate the real world and to assure the researcher full control of all the parameters implied. VR constitutes a highly flexible tool, which makes it possible to program an enormous variety of procedures of intervention on psychological distress. In fact, VR can play an important role in psychotherapy as a particular form of supportive technique, contributing to the therapist–patient relationship as well as enhancing the therapeutic environment for the patient.

In particular, a key advantage offered by VR is the possibility for the patient to face a fear or to manage successfully a problematic situation related to his/her disturbance. As noted by Botella (78), nothing the patient fears can “really” happen to them in VR. With such assurance, they can face his/her fears, freely explore, experiment, feel, live, and experience feelings or thoughts. VR thus becomes a very useful intermediate step between the therapist's office and the real world. Using VR in this way, the patient is more likely not only to gain an awareness of his/her need to do something to create change but also to experience a greater sense of personal efficacy.

Even if the clinical rationale behind the use of VR is now clear, much of this research growth, however, has been in the form of feasibility studies and pilot trials. As a result, limited convincing evidence coming from controlled studies of the clinical advantages of this approach exists. Up to now, the clinical effectiveness of VR was verified in the treatment of these seven disorders: acrophobia (79–81), spider phobia (82), panic disorders with agoraphobia

(83,84), body image disturbances [(85), see Fig. 10], binge eating disorders (86,87), acute pain (88,89), post-traumatic stress disorders (90), and fear of flying (91–95).

4.2.2. VR in Medical Rehabilitation. One of the newest fields to benefit from the advances in VR technology is that of medical rehabilitation. In the space of just a few years, the literature has advanced from articles that primarily described the *potential* benefits of using such technology to articles that describe the development of actual working systems (39,96–103).

A first area in which VR is used is the one of motor rehabilitation. In motor rehabilitation, the repeated practice must be linked to incremental success at some task or goal and supported by motivation to tolerate the extensive practice periods (99,104).

VR provides a powerful tool with which to provide participants with all of these elements—repetitive practice, feedback about performance, and motivation to endure practice (105). For this reason, VR has been used in different rehabilitative areas including stroke rehabilitation (upper and lower extremity training, spatial and perceptual-motor training), acquired brain injury, Parkinson's disease, orthopedic rehabilitation, balance training, wheelchair mobility, and functional activities of daily living training (106).

Another area in which the use VR is explored is cognitive rehabilitation (107). The main focus of the research performed to date has been to investigate the use of VR in the assessment of cognitive abilities. In this area, VR assessment tools are effective and characterized by good psychometric properties (108–112). Nevertheless, a trend now exists for more studies to encompass rehabilitation training strategies for specific disabilities (113,114): learning disabilities, executive dysfunction,



Figure 10. A VR system for the treatment of body image disturbances (courtesy of the ATN-P. Lab, Istituto Auxologico Italiano, Milan, Italy).

memory impairments, spatial ability impairments, attention deficits, and unilateral visual neglect.

The main advantage of using VR in cognitive rehabilitation lies in the possibility of ecologically valid and dynamic training: It provides precise performance measurements and exact replays of task performance and has the flexibility to enable sensory presentations, task complexity, response requirements, and the nature and pattern of feedback to be easily modified according to a user's impairments. This flexibility can be used to provide systematic restorative training that optimizes the degree of transfer of training or generalization of learning to the person's real world environment (100).

In conclusion, even if different case studies and review papers suggest the use of VR in medical rehabilitation, more research is required to support this position.

5. SAFETY AND ETHICAL ISSUES

The introduction of patients and clinicians to VEs raises particular safety and ethical issues (4). In fact, despite developments in VR technology, some users still experience health and safety problems associated with VR use (115). The key concern from the literature is VR-induced sickness, which could lead to problems (116), including:

- symptoms of motion sickness;
- strain on the ocular system;
- degraded limb and postural control;
- reduced sense of presence; and
- the development of responses inappropriate for the real world, which might lead to negative training.

The improved quality of the VR systems is drastically reducing the occurrence of simulation sickness. For instance, a recent review of clinical applications of VR reported instances of simulation sickness are few and nearly all are transient and minor (97). In general, for a large proportion of VR users, these effects are mild and subside quickly (115).

Nonetheless, patients exposed to virtual reality environments may have disabilities that increase their susceptibility to side effects. Precautions should be taken to ensure the safety and well being of patients, including established protocols for monitoring and controlling exposure to virtual reality environments.

Strategies are needed to detect any adverse effects of exposure, some of which may be difficult to anticipate, at an early stage. According to Lewis and Griffin (116) exposure management protocols for patients in virtual environments should include:

- screening procedures to detect individuals who may present particular risks;
- procedures for managing patient exposure to VR applications to ensure rapid adaptation with minimum symptoms; and
- procedures for monitoring unexpected side effects and for ensuring that the system meets its design objectives.

Finally, the effect of VEs on cognition is not fully understood. In a recent report, the U.S. National Advisory Mental Health Council (117) suggested that "research is needed to understand both the positive and the negative effects [of VEs]... on children's and adult's perceptual and cognitive skills." Such research will require the merging of knowledge from a variety of disciplines including (but not limited to) neuropsychology, neuroimaging, educational theory and technology, human factors, medicine, and computer science.

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