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Immersive training systems: Virtual reality and education and training

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Abstract. This paper provides an introduction to the technology of virtual reality (VR) and its possibilies for education and training. It focuses on immersion as the key added value of VR, and analyzes what cognitive variables are connected to immersion, how it is generated in synthetic environments, what immersion is, and what its benefits are. The central research question is the value of tracked, immersive visual displays over non-immersive simulations. The paper provides a brief overview of existing VR research on training and transfer, education, and procedural, cognitive and maintenance training.

In the half dozen years since a previous thorough overview of intelligent tutoring and computer-based instruction (Nickerson & Zodhiates, 1988) the change of technologies has been breathtaking. Although we knew back then that what we were doing on expensive Lisp machines would soon be possible on ordinary personal computers, it is still unnerving to see not only that it is now possible, but that so much more is possible. The virtual reality (VR) technologies that have transformed the landscape in the intervening years (e.g. Rheingold, 1991) offer unique new viewpoints on the core goals of training and education. What distinguishes VR from all preceding technology is the sense of immediacy and control created by immersion: the feeling of "being there" or presence that comes from a changing visual display dependent on head and eye movements. This paper will provide an introduction to the technology of VR and its possibilities for education and training. It will focus on immersion as the key added value of VR, and begin to analyze what cognitive variables are connected to immersion, how it is generated in synthetic environments, what immersion is, and what its benefits are. It is clear that a principled program of research is needed to uncover the instructional conditions that VR is best suited for, over other available media and technologies, if this new technology is to be used wisely and effectively. The central research question is the value of tracked, immersive visual displays over non-immersive simulations. The paper will provide a brief overview of existing VR research on training and transfer, education, and procedural, cognitive and maintenance training. It will close with an examination of important future issues: augmented reality, networked VR, edutainment, authoring systems, and equity.

What is VR?

There really are two kinds of VR, although in some ways they are complementary and indistinguishable. The two basic varieties are sensory immersive VR and text-based networked VR. This paper will deal mainly with visually immersive VR, the kind that makes your view of the world change when you move your head, and call text-based networked VR "Cyberspace", to distinguish it pragmatically here. Although both are very useful for education and training, Cyberspace is better handled as an aspect of distance learning (Hunter, 1993). Another variety of VR, desktop VR or "fish tank VR" is not immersive (Ware, Kevin & Kellogg, 1993), and so it is treated as another form of simulation technology in this paper. It may have a special use for abstract visualization. In some sense, though, it is similar to immersive VR, except that it partitions a smaller amount of the surrounding space than wide field of view (FOV) VR. No kind of VR was explicitly mentioned by Nickerson and Zhodiates such a short time ago as 1988. Now there are many books available on the topic, ranging from popular anecdotal overviews (e.g. Krueger, 1991; Rheingold, 1991), collections of research papers (Benedikt, 1991; Earnshaw, Gigante & Jones, 1993; Ellis, 1991; VRAIS'93, 1993; Wexelblatt, 1993), discussions of the social and educational implications of the technologies (Laurel, 1991; Turkle, 1993), analyses of the educational implications (Middleton, 1992), overviews of the hardware and software technologies (Pimentel & Teixeira, 1992), and stories of homebrew VR (Jacobson, 1994), or detailed scientific documentation (Kaslawsky, 1993).

Immersive VR

Immersive VR can be defined by its technology and its effects. Its primary effect is to place a person into a simulated environment that looks and feels to some degree like the real world. A person in this synthetic environment has a specific sense of self-location within it, can move her or his head and eyes to explore it, feels that the space surrounds her or him, and can interact with the objects in it. In immersive VR, simulated objects appear solid and have an egocentric location much like real objects in the real world. They can be picked up, examined from all sides, navigated around, heard, smelled, touched, hefted, and explored in many sensory ways. The objects can also be autonomous (especially if they are other people) and interact with the virtual voyager, or respond to voice commands (Middleton & Boman, 1994). The fundamental limitation to all these effects is in the computational technology that supports them.

The technology of VR

The technology of VR is rapidly changing and improving within a very active research community (VRAIS'93, 1993). The following sections discuss some of the more important components of this technology for current working environments. The core technology that makes immersive Virtual Reality possible, the head mounted display (HMD), is progressing particularly fast, with projections common that eyeglass-size and weight HMDs will be available by the turn of the century (Chien & Jenkins, 1994).

HMD

The essential ingredient of VR is a tracked head-mounted display (HMD) that lets you see new views of the visual world as you move your head. Wearing an HMD, one can look around and see the rest of the simulated world just like in the real world. Current image generation computers are limited in their ability to create a realistic, changing world. Special image generators cost hundreds of thousands of dollars, and the special lightweight, high resolution displays can be equally expensive. Current microcomputers can realistically generate only a few thousand polygons per second, while it has been estimated that nearly a billion polygons per second may be needed for near realism. These limitations not only lead to low resolution and cartoon-like shapes, they also lead to long lags between changes in the head position and updates of the display. Narrow fields of view (often about half the normal field of view of 180 degrees) lead to distortions of perceived space, to inaccurate self-localization (Psotka, Davison & Lewis, 1993), errors in the judgement of distances (Henry & Furness, 1993), and simulator sickness (feelings of discomfort that can range from mild eyestrain and headaches to nausea and vomiting) (Kennedy, Lane, Lilienthal, Berbaum & Hettinger, 1993).

Tracking

An unobtrusive tracking mechanism (magnetic, mechanical, infrared, gyroscopic, sound, or based on many innovative alternatives) registers any head motion and provides the signals to a computer to make the required changes in viewpoint in the modelled display. When your head moves, the visual scene changes. The result is a change of viewpoint just as if the eyes and head had moved in the virtual world. In advanced systems the scene changes when your eyes move. Such eye tracking is often used to provide a more detailed "fovea" or Area Of Interest (AOI) display (Warner, Serfoss & Hubbard, 1993) of high resolution imagery that tracks the viewpoint. Any of these tracked displays usually result in a compelling sense of "being there", of being immersed in the simulation as if it is a real world. Long lags between any user's action and the resulting computed change in the display unfortunately often destroy this illusion and can lead to simulator sickness.

Gestures and force feedback

Gloves to gesture and interact with objects, and force-reflective feedback all add to the compellingness of the experience. They add to the willingness of a participant to suspend disbelief so that they can become immersed, but the main core of the experience is still primarily visual. Tactile reinforcement of the presence of an object, its shape, weight, solidity, and texture, adds considerably to the experience. Force feedback about the collisions with objects is a fundamental aid to navigation in VR: It prevents you from going through walls and floor, and other objects. Otherwise such sudden unnatural transitions often lead to disorientation and confusion. Gestures based on sensing of hand position and shape provide a natural means for interacting and communicating with the computer. For instance, one can select a distant object simply by pointing at it. Sometimes this selection is facilitated by having a ray extrude from a finger to the object. Others have suggested that one should be able to select objects by throwing something at them.

Stereo sound

Localizing objects from stereo sound adds to the sense of presence and immersion. Unfortunately, accurate localization depends on the shape of each individual's pinna or outer ear, so only ambiguous localization is currently possible.

Voice synthesis and recognition

Voice input and output capabilities are progressing rapidly and may soon be added to general VR environments, but remain currently largely unexploited. Magee (1994) has used them effectively in a VR training simulator for Navy ship commanders. Middleton & Boman (1994) have conducted a practically and theoretically ground breaking study of the conditions in a VR environment where voice recognition is useful. They observed that voice is best used for discrete changes in the environment, such as "Put me near object X", but not as good for continuously varying dynamic dimensions such as the direction or speed of one's flight.

Smell

There are many different ways to use odors to create a striking sense of presence. The technology of delivering odors has been well-developed (Varner, 1993) in trials at Southwest Research Institute. The system uses a microencapsulation technique that can be dry packaged in cartridges that are safe and easy to handle. Human chemical senses such as taste and smell create particularly salient memories. They are also useful for alerting us to danger, sexual arousal, and emotional experience.

The psychological experience of immersion

In spite of the many technological limitations, many VR environments easily create a compelling sense of "being there", of presence or immersion. The psychological and human interface issues that affect immersion are beginning to be analyzed by several researchers (Barfield & Weghorst, 1993; Psotka & Davison, 1993; Psotka & Calvert, 1994; Slater & Usoh, 1993). Clearly the burdensome equipment and limited motion often stir feelings of claustrophobia to reduce the sense of immersion, and open the way to simulation sickness (cf. Kennedy, Lane, Lilienthal, Berbaum & Hettinger, 1992).

Immersion seems to be facilitated by the ability to control attention and focus on the new VR to the exclusion of the real world. Being able to see parts of one's own body, even in cartoon form, adds to the experience. It also depends on the use of a good visual imagination. There is a great range of individual differences in the experience of immersion in VR environments. The technological limitations are largely responsible, but temperamental differences among individuals result in different reactions to these limitations. Perhaps if the technological limitations of burdensome equipment, lack of detail, and slow computers were overcome, these individual differences would disappear. But some difficulty may still remain to destroy the illusion, because voyagers will always possess the knowledge that it is all virtual. Even slight disturbances in the VR environment, such as obtrusively measuring heartrate, destroy the experience (Psotka & Calvert, 1994; See Figure 1).

The benefits of immersion

The engagement and excitement that is part of the VR phenomenon is an obvious candidate for exploitation in education and training (Bricken & Byrne, 1993). The motivation and mindful engagement (Salamon, Perkins & Globerson, 1991) that comes from this environment stems not only from the novelty but from the challenge, interactivity, realism, fantasy, cooperation, and immersion that are natural extensions to the benefits of games and simulations (Malone & Lepper, 1987). Parts of this engagement come from the thrill of new technologies, but there is a more enduring and valuable component as well: VR is an empowerment technique that opens many new paths for learning (Pantelidis, 1993). Gay & Santiago (1994) report that high schools have effectively used VR to stimulate interest in algebra, geometry, science, and the humanities. This was done using only the crudest equipment. The unique capability that VR offers to the mix of instructional games, simulations, and microworlds is its ability to create immersion.

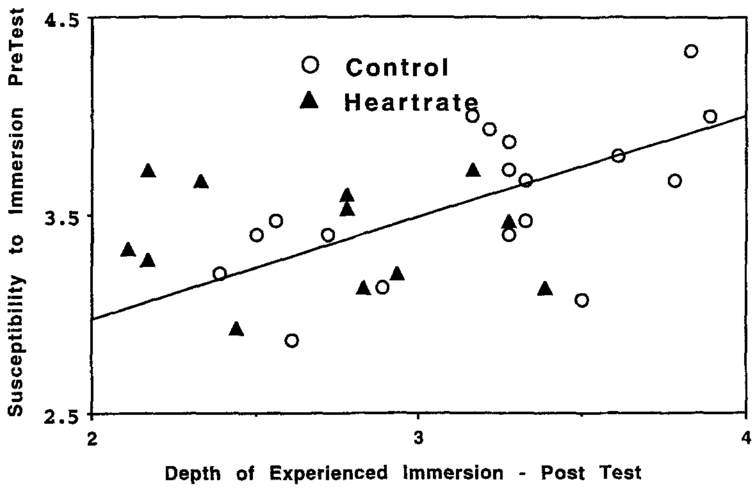

Figure 1. The reduction in depth of immersion experienced by a group whose heartrate was measured during their immersive experience.

VR provides a paradigm shift from previous interactive computer technologies because it permits all human senses, especially the most communicative, vision, to be used in natural ways that evolution has best prepared us to use them. VR should not be seen as just another technology for human-computer interaction; it provides a fundamentally different mode of communication between computer and person, between symbolic form and mental representation; and between collaborators in conceptual worlds. VR replaces interaction with immersion; it replaces the desktop metaphor with a world metaphor; and it replaces direct manipulation with symbiosis.

VR augments learning with experience. This paradigm shift is a result of the compelling motivation of the interaction when real time actions can be interpreted symbolically and coordinated procedurally in body and mind. This coordination and communication can occur across distributed networks or with fictional places so that realistic and abstract spaces can be shared. And agents and objects can be represented in novel multidimensional formats in these shared spaces to achieve a kind of multisensory integration that is akin to synaesthesia, and to promote learning. If these uses of VR for education and training are to be fulfilled, however, much needs to be learned about the benefits and drawbacks of VR, and many advances in the technology of immersion need to be made (Durlach, Aviles & Pew, 1992). If we are to know how best to use VR in the mix of media and technologies available for instruction, we must create a principled path of research to discover the unique strengths and benefits of immersion for learning and instruction.

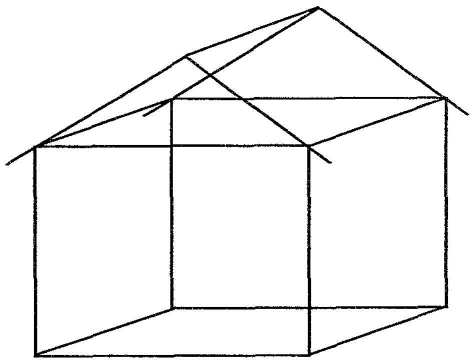

Figure 2. A demonstration of the ecological validity of our perceptions, and the role of experience in determining point of view. A Necker Cube with a "roof". Imagine looking "down" at it from above, then "up" at it from below. It is much more difficult to see it from below, since we generally see houses or house models from above or from straight on; never from below ground.

Immersion and visual perspective

The most direct and compelling benefit that immersion offers to the cognitive interpretation of the world is a reduction in conceptual load because of the simplifying directness of perception of the virtual world. In most interaction with simulations, pictures, photographs, and line drawing representations, a human observer automatically constructs a virtual self, a viewpoint that enters the space of the drawing as if a human observer were there (Kubovy, 1986). Only very rarely is this virtual self and the real self in the same perspective location (Psotka, Davison & Lewis, 1993). For example, you can hold the picture of the modified Necker Cube in Figure 2 below, high above your head, and yet still see the outline as if you were above it, looking down at it. In other words, you have created a virtual self looking down at the figure even though your real self is looking up at it. In most interaction with pictures or simulations this extra load of another virtual self has to be carried around and used to interpret the picture. It acts to make the experience less direct and reduces the cognitive resources available to carry out problem solving and mental representation of other issues.

Examining Figure 2 for a while should lead you to see reversals of perspective and points of view. You cannot simultaneously see the figure as a house seen from above and as a house seen from below; but you will find yourself seeing those two different objects alternate. If you experience some slight discomfort with this, you will appreciate the complexity of the visual and perceptual analysis needed to carry these interpretations out. There must be some additional conflict as well between these alternative perceptions and the third and more realistic perception that you are fixed in space looking at a piece of paper with this figure before you.

Although photographs and more detailed representations do not alternate as unambiguously as the Necker figure, they do have the same additional complexity of generating a conflicting point of view. This is a processing difficulty that is often overlooked when the value of pictures and figures for learning is being analyzed, but it should have measurable learning effect, that can be overcome with a well-designed virtual environment.

Allocentric viewing

Adopting an alternative viewpoint as when one views a picture and enters the space of the picture, seems relatively straightforward, but it may involve some very difficult cognitive processes and transformations. One indication of the difficulty of the task comes from the results of Psotka & Lewis' (1994) experiments on the effects of field of view (FOV) on distance judgments. In the initial part of this experiment students judged their distance from the viewing monitor by placing a mark on an overhead view of the room in which they sat. The resulting scatterplot of judged distances as a function of real distance from the monitor is somewhat non-linear and shows very large dispersion for such a simple task (see Figure 3). This large variability is a good indication of just how difficult the task of creating an allocentric view of one's situation is.

Immersion and field of view (FOV)

The accurate location of one's sense of self (one's egocenter) in a geometric space is of critical importance for immersion. Furness (1992) and Howlett (1990) report that immersion is only experienced when the field of view (FOV) is greater than 60 degrees, or at least in the 60 to 90 degree FOV range. Why this should be so is not understood, nor are there theoretical frameworks for beginning to understand this phenomenon. Immersion environments are notorious for producing motion sickness, and an inaccurate location of virtual egocenters may be implicated in this noxious effect. Jex (1991) reports that simulator sickness is hardly ever felt with FOV less than 60 degrees (the complement of immersion FOV). This effect may be related to the nonlinear compression of 140 degrees into an 18 or 45 degree FOV. This distortion effect needs to be investigated separately to determine how sensitive viewers are to FOV and compression-based distortions, pincushioning, and barrelling. Relationships with self-motion studies dealing with vection (stimulus induced feelings of self-motion) also are strongly dependent on FOV, with larger fields much more powerful in inducing optokinetic vection effects (Wertheim, 1993; Wolpert, 1990). Perhaps a key variable is the quality of immersion and the accuracy of self-localization. Informal comments by users of immersion

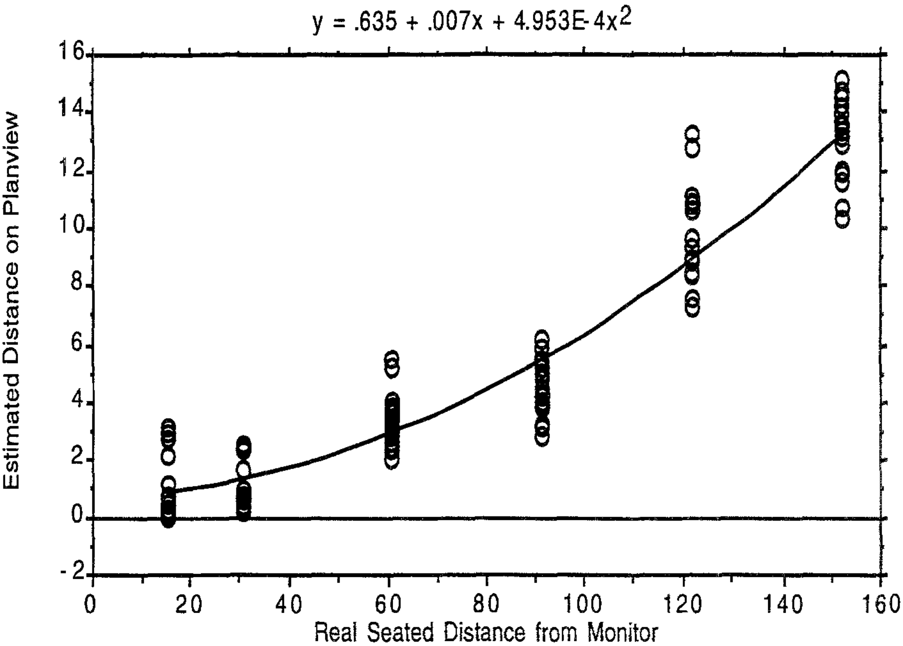

Figure 3. Estimated distance marked on a planview drawing as a function of actual seating distance from the experimental monitor.

environments have yielded many descriptions of surprising errors of self-localization. Recently Psotka & Lewis (1994) have discovered that the most veridical sense of involvement in a VR comes with the wide FOV projection, even if the display is not wide. Their data suggest that for narrow FOV, the projected FOV should roughly split the difference between the physical FOV of the optics and 180 degrees. They also discovered that judgements of distance in a virtual space are markedly nonlinear when the field of view is less than 70 degrees (see Figure 4).

Designing a VR so that immersion and self localization are seamless turns out to be difficult given the limits of current technology. It is not possible to create wide FOV HMD displays at reasonable cost, but there are psychological components that offset this difficulty to a degree. Adaptation to the distortions of a VR environment is relatively rapid (Dolezal, 1982) so that errors in self location diminish rapidly with time; and forgetting the real world and your place in it occurs quickly, so that soon the voyager in a VR has only to deal with her or his location in the VR, not the simultaneous burden of maintaining one's location both in the VR and the real world.

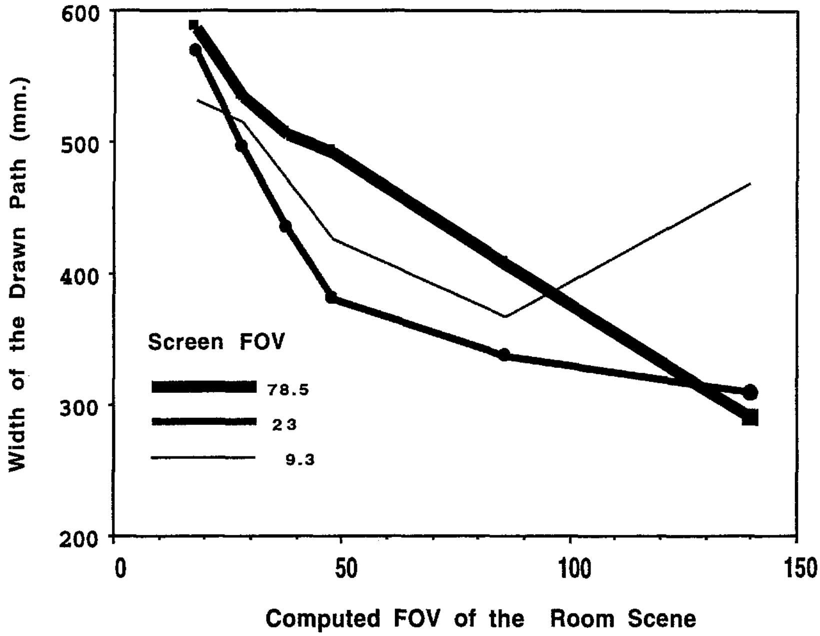

Figure 4. The Width of the path of a simulated camera drawn by 50 Ss seated at 6 different distances from a monitor, as a function of 3 different computed fields of view of the scene.

Viewpoint manipulation

A clear implication of this research is that it is possible to manipulate the apparent location of one's virtual egocenter in many complex and mutually interacting ways. We do not understand how this is to be done, nor can we yet contrive good implementations in training, or command, control, and communications for carrying it out. The artists of the Renaissance and Chinese landscape art offer some interesting clues about possibilities. Take for instance Michelangelo's Last Judgement in the Sistine Chapel. In this stunning representation, there is a grand conceptual unity of action encompassing huge areas of space with masses of saved humanity struggling upwards on the left, and the damned ricocheting down on the right. In the center there is a massive stillness. What is dramatically unique about this conception is that there is no unique viewpoint portrayed by the artist. Every creature is at the center of the visual field, and yet the artist has subtly contrived to unify the whole without the dominating constraint of a unique point of view. How has he done this? In part, he has created local areas of fixed viewpoint, so that the central figure creates peripheral views of the surrounding figures. Without this device the figures would all be flat, as if seen from infinity. Yet, he must have distorted the projection so that the surrounding figures are not as peripheral as they would have been with a true isomorphic projection. In any event, the Last Judgement itself is unified both by projection and by thematic constraints that affect projection in complex ways.

It is not clear how a computer model of this image ought to be carried out. Certainly, no modelling system can combine the multiple viewpoints and integrate them pleasingly the way Michelangelo intuitively did. Instead of the strictly projective view of dataspaces as cities and rooms that we currently have, we might be able to lay out dataspaces that gives equal emphasis to more distant and proximal areas, much as a Chinese landscape does. Clearly there are many potential uses for such a distortion of virtual space that range from command and control to communication and training.

VR and motion platforms

Visual information is not sufficient for immersion: another key ingredient is accurate vestibular information, synchronized with the cognitive motion plans and with visual changes as the head turns, nods, or accelerates. If visual information were sufficient, there would be no need for head mounted displays. The importance of motion for immersion in VR stands in unexplained contrast to the consistent lack of importance of motion platforms for training. There are no transfer of training data that support use of motion-based simulators (Boldovici, 1993).

There may be many reasons for these lack of data; both because motion may not help in some cases, and because experimental techniques to determine motion's benefits in simulators are either inadequate or do not exist. This is in sharp contrast to VR experiences where motion is critical to immersion and the accurate and immediate recall of location of novel objects (Pausch, Shackelford & Proffitt, 1993). Without motion correlated with visual change, the central and defining feature of VR – presence or immersion – is absent. In VR environments a person has to generate the motion to create the feeling of presence in most current applications. You have to move your head, or turn your body. Drawing on this experience, it may be appropriate to infer that motion platforms may be needed when the VR is not just a first-person immersion, but even when it is a vehicle-based immersive environment, like SIMNET (a tank training VR). Kinaesthetic stimuli are so important in VR that it may be more appropriate to call VR "kinaesthetic visualization" to emphasize the multimodal, dual nature of the immersive experience.

In VR simulations the contrast between a tracked display and an ordinary stationary display is like night and day. Without the kinaesthetic and vestibular sensations that tracking the viewer's motion correlates with visual change, the images remain a dynamic movie of a tour through an environment. It is possible, just barely for most people, to build a model of the environment in this untracked mode; but add tracking, and kinaesthetic visualization creates a powerful Gestalt out of the frames of experience. This Gestalt then surrounds and fills the space around a viewer in a complete mental model of the environment, that is very useful for orientation, memory of locations, and navigation in general.

This kind of unification and chunking of the mosaic of images that we get as we move through our surroundings goes on effortlessly all the time as we look around in our environment. Its importance for immersion is undoubted, even if we really don't understand exactly how it works yet; or what its limitations are.

Motion cues

An exemplary case where motion platforms may prove very useful is the gunner in a tank simulation. For instance, even after going through a briefing that explained the scenario, starting with an overhead view (a planview) of the events, and trying to work out a thorough mental model of the scenario, within a minute of starting the simulation I was lost. I knew the tanks were out there somewhere, but I had no idea where I was looking. I was disoriented. All I saw out the gunner's sight was a series of disconnected images; not even a mosaic; certainly not a Gestalt. I suspect that the more complex and unfamiliar the outside environment is; the more realistic it is; the more important kinaesthetic visualization becomes.

Motion cues provide a powerful support for grouping and chunking visual images seamlessly. This is an important new implication of motion cuing that research with VR makes obvious. It suggests new importance for motion platforms for simulators, and may even give us a way of showing a transfer of training benefit that is real, large, and worth the cost. VR makes it clear that motion platforms can be useful when we need spatialized knowledge; when we need to remember where things are when they move out of sight.

One fruitful paradigm we have identified for research to uncover visual-vestibular interactions, we call "cognitive tracking". In "cognitive tracking", instead of having an automated tracking device monitor head motion, we ask subjects to "play camera", pretend that they are the camera and move the head mounted display in synchrony with changing video displays. In results that will be examined in greater detail in current experiments, it was apparent that accurate synchrony of spatial motion of the head with changing visual perspectives results in improved immersion over no coupling between head motion and visual display change, even when it is cognitively clear that there is no causal relation between head motion and changes in the visual display. This has some direct implications for motion platforms in many simulators, providing evidence for their importance in tank and helicopter simulators. Although past research has shown little benefit of motion platforms for training, there may be many reasons to explain why this benefit could not be found (Boldovici, 1993) and experimental results from VR shed a new light on the importance of motion. By improving our understanding of visual immersion we can lay the groundwork for improved command, control, communications, and training (Sebrechts, Psotka & Knott, 1994).

VR, instruction, and transfer

Several early studies emphasized the potential of VR technologies for training (Durlach, Aviles, Pew, DiZio & Zeltzer, 1992; Schlager, Boman, Piantanida, & Stephenson, 1992). Recently, some empirical data have been collected on the relative instructional effectiveness of VR, as well as transfer of skill to the real world. For instance, Regian, Shebilske & Monk (1992) showed that people can, indeed, learn to perform certain tasks from virtual environments (e.g., console operations, and large-scale spatial navigation). Next, knowledge and skill acquired in a VR have been shown to transfer to performance in the real world. Regian, Shebilske & Monk (1993) found that: (a) VR console operations training can transfer/facilitate real world console operations performance, and (b) VR spatial navigation training successfully transfers to real-world spatial navigation. This finding is corroborated and amplified by Goldberg (1994). In contrast to these findings, however, those reported by Kozak, Hancock, Arthur & Chrysler (1993) showed *no* evidence for transfer of a "pick and place" task from VR to the real world. However, the criterion task used in that study may have been too easy, and thus the data were actually inconclusive.

Jense & Kuijper (1993) have used VR in a trainer for air defense artillery using a hand-held portable rocket device called a Stinger. Prior training for this device has been carried out in expensive, large dome projection systems with powerful computers and mechanical systems. A HMD can provide equivalent training experiences at a fraction of the cost. Although there are still many limitations of the HMD (resolution, lag, disorientation, etc.), the system was developed in only a few days, and can provide familiarization with many basic skills before they are refined in the very expensive dome-based simulator. Since this trainer really only provided a demonstration of the system potential, no real evaluation was carried out.

Goldberg (1994) reports on experiments at USARI Simulator Systems Research Unit (Moshell, Blau, Knerr, Lampton & Bliss, 1993) that show the value of tracked displays for learning to navigate through a complex building. In their experiment subjects studied route directions and photographs of landmarks, either with or without a map of the building. They then either rehearsed in the building, or with a HMD and the model, or with verbal directions. They were then tested with actual traversals of the building. The real building produced fewer wrong turns (1.1) than the virtual model (3.3) but both were significantly better than the verbal rehearsals (9.2). The virtual environment was almost as effective as the real building for learning route information.

Johnson (1994) conducted research which required soldiers to use VR technology for terrain familiarization training, using either the Hanchey Army Heliport (HAH) located on Fort Rucker, in Alabama, or neutral sections of Arizona. The soldiers trained on the heliport VR unerringly guided him to points he requested in the real world. In other words, they were able to learn external terrain information from self-guided exploration of a virtual environment and transfer this knowledge to the actual, physical environment that had been modeled. Soldiers trained on the Arizona database, not surprisingly, knew nothing about Hanchey and could not find any of the requested points.

An even more dramatic indication of the power of VR for training comes from the research of Magee (1993) at the Defence and Civil Institute of Environmental Medicine. Using virtual reality devices such as HMDs, along with voice recognition, computer networking, and expert systems they created an exploratory system as a proof of concept for training junior navy officers the conning skills required to keep ships in formation during maneuvers and battle drills. The system provided accurate hydrodynamic and physical modeling of the conned vessel. Instruments were dynamically modelled to provide accurate feedback. A surrogate bridge team, modelled in the computer with expert systems technology, responded to voice recognition commands by the trainee with appropriate verbal responses and information. This feature provided large cost savings by eliminating the need for many real bridge personnel. The voice recognition system was also used to record feedback by the training officer who individually tutored the trainee. The system provides a complete audit trail of all interactions for a detailed after action review.

The distinguishing feature of this simulator and trainer beyond more traditional systems is its ability to spatialize the location of ships in the maneuver around the trainee. The virtual view through the HMD provided a three-dimensional format that places the ships and their paths in a realistic space that surrounds the trainee. Added on top of this realism is the ability to leave visible and enduring wakes or trails for each ship. These wakes can be compared to standard or textbook solutions that can be superimposed on any view. These standard solutions also automate the paths of ships not controlled by the trainee. A plan view display is also available to the student to help transfer learned skills from the VR environment to more traditional two-dimensional learning environments, such as paper or computer screens.

A field trial of the system evaluated it against training conducted using traditional techniques. The VR simulator provided significantly improved training at reduced cost. This landmark project provides excellent evidence for the training advantages of VR systems combined with traditional computer-based training and novel intelligent tutoring technologies

VR and intelligent tutoring systems

The role of an intelligent tutor can be implemented in many new ways in a VR. As a ghost presence, the tutor can interact with a student through digital speech, through text that floats in the air, or through replays. As an embodied presence, the tutor can vary in reality from a stick figure to a realistic manikin, with facial expressions and voice. The possibilities envisioned for intelligent tutoring systems are both made more concrete and expanded by the potential of VR.

VR and simulations

The uses of simulations in past intelligent tutoring systems (e.g. MACH-III, Steamer, TRIO, and IMTS) were already exploring the edges of VR graphically (Psotka, Massey & Mutter, 1988). Distance learning experiments and digital libraries were already understood as sources of electronic learning. In fact, the first MUDs (multi user dungeons) were being used by veteran game players. Hypertext systems were well-developed in the research community and just beginning to appear on the consumer market.

The language of VR is most easily and directly connected to the traditional concept of microworlds. Microworlds were also routinely called artificial worlds, with the important property of reality distortion for educational purposes. The ideas of combining these electronic exploratoria with tutorial capabilities, agents, slaves, and coaches, in networked or standalone forms, were also well-developed if not exactly well-implemented (Lawler & Yazdani, 1987). It may be only one small conceptual step from microworlds to artificial worlds and virtual worlds.

An appropriate quote from Nickerson & Zodhiates (1988, p 301) provides a good summary of VR technology:

> One can easily imagine a facility that would permit the user to move readily among various representations of a given entity (structure, process, event) examining it from different perspectives at different levels of detail, accessing clarifying or amplifying information that itself is available in a variety of forms . . .

There are clearly many precursors to the use of VR for education and training. What then does VR add to this picture?

Situated learning through VR

VR changes the potential relationships between learning and experience. VR potentially highlights and leverages the role of perception, particularly visual perception, in learning. The relationship between experience and abstract pedagogy is a briar patch of thorny questions. Recent theoretical harangues on the nature of situated learning have laid a kind of groundwork for VR by arguing for an epistemology of learning based on experience (Brown, Collins & Duguid, 1989). Experience is both social and perceptual (Vygotsky, 1978).

Although the perceptual aspects of experience are obviously important, it is easy to assume that there are no difficulties or impediments to learning from existing visual representations and simulations, like photographs, movies, and static drawings. That there are many difficulties is easy to downplay and overlook in modern learning environments. Most of us are experts at interpreting visual representations on printed pages (figures, graphs, photographs, icons, etc.). It is easy to forget the difficulty we once had interpreting scattergrams and line graphs. Yet, we know from many studies of expertise that those difficulties never completely go away. For younger learners these difficulties may be even more pronounced. VR can remove these difficulties to a degree and make information more accessible through the evolutionary prepared channels of visual and perceptual experience.

Central to this perceptual experience of VR is the poorly understood phenomenon of immersion or presence. The educationally leveraging components, processes, and effects of immersion have yet to be determined. Preliminary insight based on the SIMNET experience provides both personal testimonials to the motivating and stimulating effects of the social and vehicle-based immersion of synthetic environments, and preliminary effectiveness data on its potency for learning and training. Although SIMNET provides an impoverished perceptual simulation of a tank in action, the cues from active social engagement of crew members' communications and the auditory and visual cues of the simulated sights provide gut-wrenching and sweaty believability. What's more, the evidence clearly shows training effectiveness (even without a curriculum) that is superior to many other classroom and simulation-based efforts (Bessemer, 1991). Research is continuing on how to make this training more effective by including surrogate crew members and intelligent semi-automated forces in the environments. The need to involve dismounted infantry, not just tanks and vehicles, is creating a research base for better computational models of agents and coaches (Badler, Phillips & Webber, 1993).

Some examples

It is easy to speculate about the advantages of VR for education and training systems, but specific examples provide a better grounding for both advantages and disadvantages.

VR and science

VR may have a role in the construction of microworlds for physics, and science instruction. Bowen Loftin and Chris Dede (1993) are creating a Virtual Physics Laboratory from the base facilities of a VR world created for NASA astronaut training. Their virtual laboratory will allow students to conduct experiments in a virtual world where everyday accidents, structural imperfections, and extrinsic forces, such as friction, can be completely controlled or eliminated. Balls bounce with complete determinism, can be measured accurately at all times and places, and can even leave visible trails of their paths effortlessly.

The believability of these microworlds hinges on the quality of the immersive experience they provide. The differences between a VR microworld and its 2D simulation counterpart appears to rest fundamentally on the results of immersion and in the different ways that students can interact with the world. Instead of moving a mouse or a joystick, they can move their own hands to pick something up. Although they might not feel the object accurately, there are enough cues to provide the "sensation" of picking things up. First, they "see" it happening, and vision clearly dominates other senses to provide a compelling illusion. Contact and force can be provided realistically with expensive force feedback devices, or suggestively with sounds, such as a "ping" that denotes collision or touching.

An education scenario: A day in the life of...

Melissa Kaplan begins her junior high school day on 4/4/2020 by rolling out of bed and donning her Ultralite™ glasses and gloves. Small emitters on them are tracked by her WallScreen™ to decide where she is and what her posture and gestures are. The WallScreen projects a stable 3D image of virtual objects around her and her Ultralites superimpose foveal high resolution detail on the objects she is examining. The padded 20 by 20 room is now empty to allow her freedom of motion except for a small robot that follows her around closely. As she picks up a virtual microscope and dissection instrument, the robot interposes various flexible objects to give her the force feedback and impression that the virtual objects are really there.

A little squeamish, Melissa needs some reassurance and instructions from her Virtual Teacher before she begins to examine the human heart. She tunes in to what her friends are doing and is pleased to see that their faces are no more relaxed than hers. She and her teacher decide who her team will be and they set to work for the next hour exploring the anatomy and system dynamics of a human heart. At the end, they each have to build a little valve as thin and flexible as possible but strong enough to resist the powerful pressures. Melissa's design wins clearly on all these constraints, and she is delighted. After a short break of tumbling and snow tag they are ready to begin some molecular chemistry. Today's lesson deals with crystalline structure and state changes. The team for today is going to look at the changes in water as it freezes. Melissa is basically curious about things and has always wondered how water could gain energy, and therefore ought to expand, but instead it contracts when it melts. As they enter the molecular simulation she can feel the atoms bouncing discretely off her. She catches a few and tries to pull them free.

Everything feels very cold and the atoms are all arranged very regularly around her. She measures their distances and the forces on them. Jason, her team member, just then pulls one of his usual stunts and lets a molecule fly at her. As she jumps aside she can feel the push and pull of all the forces she has released, and a great fissure cracks open beside her. As warm air rushes in she sees the crystals dissolve into a chaos of atoms, each more compact than the larger crystals it replaced. There it is: the mystery of ice. Clever of Jason to think of this simple way to melt the crystal, and it was fun too. After lunch, they do some orbital mechanics. Melissa never tires of the experience of returning from orbit where they conducted the experiments. The designer for this simulation has created some stunning experiences. For instance, as they glide down to earth in a straight line, the simulation gives them a view of the setting sun that gives them the powerful but brief impression that the sun truly is standing still and the earth is moving, all the way down to a few meters off the ground. It is the only time in her life when Melissa can truly and experientially free herself from the terracentric impression that the sun is moving around the earth, while she is standing on the earth. Because she experiences it and does not just think it cognitively, abstractly, it has a profound and lasting effect on her perception of herself and her place in the universe, without leaving her home.

A maintenance training scenario: MACH-III

In 1988 an intelligent training system for radar maintenance, MACH-III, was first created. The complexity of a radar is stunning. The training manuals do little to relieve the unwieldy intricacy of its details. The thick folio manuals are unaffectionately known as "branch and get lost" manuals. These are basically engineering documents that divide the radar along design lines, largely inappropriate for functional troubleshooting.

In MACH-III, the qualitative simulation of the loops and connectivity of the radar provided the heart of the approach to making expert radar knowledge accessible and manageable. But even its complexity was staggering. And worse still, it was entirely abstract. The object oriented graphics system dealt with loop and chain structures in the radar; with information flow, sources and propagation of noise, and signal flow. These abstract relationships were visualized with dynamic pipelike wires with visible flow patterns. But the patterns too were abstractions that ran in circles or rectangles, not in the spaghetti-like interconnections of the real equipment.

Virtual reality technologies could make a real difference in the situational grounding of these qualitative models (Acchione-Noel & Psotka, 1993). It could allow instructors to begin with the basics of what part is where and what it is called; and then move on to the more demanding aspects of building a good mental model for troubleshooting right in the same environment (Schlager et al., 1992). Augmented reality technologies could enhance the training effectiveness of the simulation greatly.

Augmented reality vs virtual reality

Augmented reality technologies project a computer image with a standard head-coupled control onto a real external object (Feiner & Beshers, 1990) The potential power of this technology in our context is that it can turn on a dangerous high power machine even when it is unplugged. Instead of worrying about the effects of radar illumination, you only have the low energy LCD (liquid crystal displays) to deal with. Imagine if you will, the power of combining the abstract functional structures that MACH-III created, with the handson experience on the actual equipment. Nomenclature of all the parts could be learned by pointing at the real equipment and having both a visual text and an aural explanation popup. Switches could be pushed, displays seen, and flow monitored through actual wires, all virtually. Popup menus can be activated on the real equipment. Real nuts and bolts could be turned and reset without all the mechanical gadgetry of sensors and activators that mockups demand.

Perceptually grounding all the abstract flow diagrams on the real equipment has a potential power for creating expert mental models that really cries out to be explored. Being able to walk around the real equipment, bang into it, and kick it in return, has an undeniable potential for scaffolding and providing support to the graduated learning of complex mental models. On this firm base, the abstract symbolic models of troubleshooting techniques and strategies could be carefully shored up to provide a solid basis for further learning in the field. In fact, the whole training enterprise could move fluidly from the classroom into the field with portable headgear.

Augmented reality limitations
The major hurdle in creating a working augmented reality system is accurate tracking and registration of the trainee's location. In order to flip switches accurately, it is necessary to track hand location to at least an inch or so. A broad array of tracking systems are now available, including magnetic, ultrasound, mechanical, optical and analog tracking devices. None of them are adequate by themselves, and a mix of systems will need to be developed. The secondary hurdle is of registering the image accurately once the trainee has been accurately tracked. Current systems raise many sensory conflicts: fixed accommodation of the lens and convergence of the eyes being primary (Rushton & Wann, 1993). Objects are not correctly localized as a result, and appear to float in space, the wrong space. The solution lies in cheap variable power lenses (currently unavailable).

Virtual reality
Some of the limitations of augmented reality training systems can be avoided by using completely symbolic representations. The entire radar can be accurately modelled in a computer graphics package. Photographs of the radar can be digitized and accurately superimposed on the model in a process called "texture mapping". A trainee can then deal with this system in much the same way as a real object, but without the physical sensations of touch and "force feedback". Tracking and localization problems are overcome, but the absence of touch and haptic stimuli is also problematic. Various techniques are available to provide some of the touch and force sensations (using pressurized gloves; producing sounds like "ping" when objects are touched; and preventing motion through objects visually) and they are effective to various degrees, but the effect of all this on learning and training is still unexplored and unknown.

A real life training example: Training NASA flight controllers

For the Hubble Space Telescope (HST) Repair and Servicing Mission in December 1993, the Software Technology Branch (STB) of the Johnson Space Center of NASA used sophisticated VR technology to train mission operations flight control and engineering personnel in their tasks to support the shuttle astronauts in space (Loftin, Kenney, Benedetti, Culbert, Engelberg, Jones, Lucas, Menniger, Muratore, Nguyen, Saito, Savely & Voss, 1994). The project represented the first effort of its kind in training large numbers of people naive to VR and, in this case, over 100 flight controllers for a NASA mission. This project was motivated by the limited access to training facilities by anyone other than astronaut personnel. The primary training goal was to familiarize flight controllers, engineers, and technicians with the location, appearance, and operability of the different components on the HST, as well as the maintenance components in the shuttle cargo bay. Training sessions and procedural guidance provided flight controllers with a VR simulation experience that provided first hand insight into the actions astronauts performed in an open shuttle bay in space. Each training session was monitored by one trainer working with an average of three trainees. Each session concentrated on one training module at a time with each trainee taking turns and performing one virtual task for that session while observing on a large monitor the remainder of the time. To incorporate intelligent training capabilities into the VR, such features as audio identification-of-object and error messages, blinking objects (for next-step prompting), and sequence management were implemented.

Once training was completed, a survey questionnaire was distributed to all trainees to gather data, including comments and suggestions, about VR and training efficacy as well as input on future VR applications. Of 105 surveys sent out, 38 forms were returned and processed. The project met and surpassed its goals. On the whole, the questionnaire responses were very positive and even enthusiastic. For instance, the overall effectiveness was rated slightly over "effective" or 4.08 (in a range of 0–5). Users found that visualizing activities enhanced understanding. At an average of 3.75, users reported just below "significant" knowledge gains from the training experience. The ability to visualize tasks (and positions of various items in the shuttle cargo bay and on the HST) had a positive impact on user's comprehension of activities and objects. The majority of comments were all very positive and ranged from just "Fun!" to being "... the neatest training tool ..." that individual had ever used. Some incidents of physical side-effects such as nausea, oculomotor problems, and disorientation resulting in mild cases of simulator-sickness were reported. Of course, these occur in real space flights too, to a much greater degree, so they may even have added to the veridicality of the experience. Several flight controllers suggested that the downlinked video data reminded them of what they had experienced in VR.

The results also suggested that many additional technologies could strengthen this experience and make it even more valuable: intelligent on line help and tutoring; force feedback; voice recognition and synthesis, and even augmented reality with the real shuttle. A combination of approaches using head-mounted displays with both virtual reality and augmented reality technologies could prove very effective.

Networked virtual reality

Every virtual world can be shared in a networked version without adding greatly to the computational burden (Loeffler, 1993; Moshell & Hughes, 1993). This means that trainees and experts can interact between schools and remote sites. Trainees and instructors can share the same experience. Trainees can work together on the same object, or they can work on the same object at the same time without being aware of each other's presence, while another invisible instructor lurks over their shoulders.

The other "person" in the networked world could also be an autonomous agent, or "cyborg", part real and part synthetic. This raises a whole new set of possibilities for a "computer coach" and explanations and guidance.

Social interface agents (Thorisson, 1993) are progressing steadily as information about how to direct gaze, when to use paraverbals (hmmm, uh ...) and to take turns in a dialogue, all become better understood. Improvements in modelling human actions and planning (e.g. Badler, Phillips & Webber, 1993) including natural language interaction, make it possible to have virtual agents available to coach and guide learner's actions worth within tutorial systems.

Networked digital spaces, such as digital libraries, will demand new techniques for navigating through these complex spaces without getting lost. Issues of how to maintain a sense of location (Benedikt, 1991) and how to best use these environments to support memory with the method of loci (Neisser, 1987) need a new body of research findings.

Other future issues

These summary suggestions only scratch the surface of the vast space of implications VR technologies offer for training. As the example of extended revisions for MACH-III suggests, the limitations of earlier systems are clearly visible in the light of the many new possibilities and challenges the rapid growth of VR technologies offers.

Authoring systems

The many difficulties in creating intelligent tutoring systems will be compounded with the need for creating synthetic spaces. At the moment the graphics environments for creating these systems still often require access to powerful programming languages like C++ in order to make them fully interactive. No authoring environments yet support the creation of spaces from within the VR itself (except for text-based VRs). Authoring environments for creating immersive tutoring systems will be another order more complex and further in the future. There are clearly implications in this for all the traditional issues of computer based instructional design (Locatis & Park, 1993). VR systems will be cost-effective for some applications at some point of time in the near future, and probably for all applications in the not-too distant future.

Spatial browsers and abstract displays

The use of VR to spatialize knowledge so that it is more accessible and orderly will reduce the current limitations of hypertext systems, and reduce the likelihood of becoming "lost in hyperspace" (Dede, 1992). VR knowledge browsers are only beginning to be developed (Fairchild, 1993) but offer great promise in education and training for making complex hierarchical structures such as troubleshooting and diagnostic trees, or semantic networks of words, much more memorable and open to inspection and browsing.

Equity

VR opens the opportunity of different kinds of educational games and environments that appeal to a broader spectrum of people. For instance, text-based VR already invites the participation of women and girls in social interaction in ways that adventure games like dungeons and dragons did not (Turkle, 1993). In fact VR provides a "new saliency on the notion that we construct gender and that we become what we play, argue about, and build." Turkle points out that MUDs are easily used for gender swapping. Within these switched gender roles, sexist expectations and overt demands that might be ignored in daily life become highly visible and reactive, and they are openly discussed. A similar point could be made about many social distinctions, such as poverty, multi-cultural differences, race, and many belief systems. VR offers a way of exchanging viewpoints that could lead to greater understanding. VR also opens the opportunity for providing handicapped or disabled people the experience of unfettered motion; or new interfaces to control the world with minimal movements.

Edutainment

The convergence of technology and entertainment has enormous potential consequences for education, particularly in the form of simulation games that have been branded edutainment, from the synthesis of video games, and educational simulations. There is a vibrant creativity in the development of these games that promise rich fantasy experiences that liberate imagination and promote probing explorations of new hypotheses and great quantities of information.

Organizational change

Increased use of digital-rich libraries over telephone with on-line digital librarians calls for fundamental structural change in education. VR technologies can provide the basis for on-line agents and for a complex metaphor and model of the library as a knowledge space.

Summary

There are many potential high-payoff areas for research and development of VR technology for education and training. VR needs to be developed as an integral part of the educational and training process, implemented alongside other traditional and non-traditional tools. It can be used for exploration and for training practical skills, technical skills, operations, maintenance and academic concerns. Teachers and trainers need to be exposed to VR in multiple ways so that they can begin preparing themselves and their institutions for future changes. Integrated scenarios for an assortment of environments and educational areas need to be developed to give educators and trainers a better view of the strengths and weaknesses of these environments; and to give evaluators a means for documenting effectiveness and formative evaluations. Digital libraries need to be constructed that take advantage of VR interfaces. Much more research is needed on the variables that control immersion and on the benefits and drawbacks of immersion so that cost-effective design compromises can be made. Finally, more extensive long term effects, both social and psychological, of these environments need to be documented and analyzed.

References

Acchione-Noel, S. & Psotka, J. (1993). *MACH III: Past and future approaches to Intelligent Tutoring*. In Proceedings of 2nd Conference on Intelligent Computer Aided Training and Synthetic Environments, Houston, TX, May.

Badler, N. I., Phillips, C. B. & Webber, B. L. (1993). *Simulating Humans: Computer Graphics Animation and Control*. New York: Oxford University Press.

Barfield, W. & Weghorst, S. (1993). The sense of presence within virtual environments: A conceptual framework, in G. Salvendy & M. J. Smith eds., *Human-Computer Interaction: Software And Hardware Interfaces*. New York: Elsevier.

Benedikt, M. (Ed.) (1991). *Cyberspace: First Steps*. Cambridge, MA: The MIT Press.

Bessemer, D. W. (1991). *Transfer of SIMNET training in the armor officer basic course* (ARI Technical Report # 120). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Boldovici, J. (1993). *Simulator Motion* (ARI Technical Report No. 961). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Bricken, M, & Byrne, C. (1993). Summer students in virtual reality: A pilot study on educational applications in virtual reality technology, in A. Wexelblat ed., *Virtual Reality Applications and Explorations* (pp. 199–217). Toronto: Academic Press Professional.

Brown, J.S., Collins, A. & Duguid, P. (1989). Situated cogniticions and the culture of learning. *Educational Researcher* 18: 32–42.

Burdea, G. & Coiffet, P. (1994). *Virtual Reality Technology*. New York: John Wiley & Sons, Inc.

Chien, Y. T. & Jenkins, J. (1994). *Virtual Reality Assessment*. A report of the Task Group on Virtual Reality to the High Performance Computing and Communications and Information Technology (HPCCIT) Subcommittee of the Information and Communications Research and Development Committee of the National Science and Technology Council (NSTC).

Curtis, P. & Nichols, D. A. (1993). *MUDs grow up: Social virtual reality in the Real World*. Proceedings of the Third Annual Cyberspace Conference, Austin: TX.

Dede, C. J. (1992). The future of multimedia: Bridging to virtual worlds. *Educational Technology* 32(5): 54–60.

Dolezal, H. (1982). *Living in a World Transformed*. New York: Academic Press.

Durlach, N. I., Aviles, W. A., Pew, R. W., DiZio, P. A. & Zeltzer, D.L. eds. (1992). *Virtual Environment Technology for Training (VETT)*. (BBN Report No. 7661.). Cambridge, MA: Bolt Beranek & Newman, Inc.

Earnshaw, R. A., Gigante, M. A. & Jones, H. (1993). *Virtual Reality Systems*. Toronto: Academic Press.

Ellis, S. R. (Ed.) (1991). *Pictorial Communication in Virtual and Real Environments*. London: Taylor & Francis.

Fairchild, K.M. (1993). Information management using virtual reality-based visualizations, in A. Wexelblat ed., *Virtual Reality Applications and Explorations* (pp. 45–74). Toronto: Academic Press Professional.

Farr, M. J. & Psotka, J. (1992). *Intelligent Instruction by Computer: Theory and Practice*. Washington, DC: Taylor and Francis.

Feiner, S. & Beshers, C. (1990). *Worlds within Worlds: Metaphors for exploring nDimensional virtual worlds*. In Proceedings of UIST '90. New York: Academic Press.

Gay, E. R. & Santiago, R. (1994). VR Projects at Natrona county, Wyoming. *Sci-VR-Apps bulletin*: May 5.

Goldberg, S. (1994). Training dismounted soldiers in a distributed interactive virtual environment. *U. S. Army Research Institute Newsletter* April 14: 9–12.

Henry, D. & Furness, T. (1993). *Spatial perception in virtual environments: Evaluating an architectural application*. In VRAIS '93 (1993). Proceedings of the IEEE Virtual Reality Annual International Symposium. Seattle, Washington.

Hunter, B. Internetworking: Coordinating technology for systemic reform. *Communications of the ACM* May: 42–46.

Jacobson, L. (1994). *Garage Virtual Reality*. Indianapolis, IA: Sams Publishing.

Jense, G. J. & Kuijper, F. (1993). *Virtual Environments for Advanced Trainers and Simulators*. In Proceedings of 1994 International Training Equipment Conference, London, May 1993.

Johnson, D. (1994). *Virtual Environments in Army Aviation Training*. Proceedings of the 8th Annual Training Technology Technical Group Meeting (pp. 47–63). Mountain View, CA.

Kaslawsky, R. S. (1993). *The Science of Virtual Reality and Virtual Environments*. New York: Addison-Wesley Publishing Co.

Kedar, S., Baudin, C., Birnbaum, L., Osgood, R. & Bareiss, R. (1993). *Ask how it works: An interactive intelligent manual for devices*. In Proceedings of INTERCHI (pp. 171–72). Amsterdam.

Kennedy, R.S., Lane, N.E., Lilienthal, M.G., Berbaum, K.S., & Hettinger, L.J. (1993). Profile analysis of simulator sickness symptoms: Application to virtual environment systems. *Presence* 1: 295–301

Kozak, J. J., Hancock, P. A., Arthur, E. J., & Chrysler, S. T. (1993). Transfer of training from virtual reality. *Ergonomics* 36(7): 777–784.

Krueger, M. W. (1991). *Artificial Reality II*. Reading, MA: Addison-Wesley Publishing Co.

Kubovy, M. (1986). *The Psychology of Perspective and Renaissance Art*. Cambridge: Cambridge University Press.

Laurel, B. (1991). *Computers as Theater*. Reading, MA: Addison-Wesley Publishing Co.

Lawler, R. W. & Yazdani, M. (1987). *Artificial Intelligence and Education.* Norwood, New Jersey: Ablex Publishing.

Locatis, C & Park, O. (1993). Some uneasy inquiries into ID expert systems. *Education and Training Research and Development* 40(3): 87–94.

Loeffler, C. E. (1993). Networked virtual reality: Applications for industry, education, and entertainment. *Virtual Reality World* 1(2): g-i.

Loftin, R. B. & Dede, C. (1993). Surreal Science. *Scientific American*: February 103.

Loftin, R. B., Kenney, P. J., Benedetti, R., Culbert, C., Engelberg, M., Jones, R., Lucas, P., Menniger, M., Muratore, J., Nguyen, L., Satio T., Savely, R. T. & Voss, M. (1994) In Proceedings of the 16th Interservice/Industry Training Systems & Education Conference to be held in Orlando, Florida on November 28–December 1, 1994.

Menniger, M., Muratore, J., Nguyen, L., Saito, T., Savely, R. T., & Voss, M. (1994). In Proceedings of the 16th Interservice/Industry Training Systems & Education Conference to be held in Orlando, Florida on November 28-December 1, 1994.

Magee, L. (1993). MARS Virtual Reality Simulator. Defence and Civil Institute of Environmental Medicine Fact Sheet G-07. North York, Canada.

Malone, T. W., & Lepper, M (1987). Making learning fun: A taxonomy of intrinsic motivations for Learning, in R. E. Snow and M.J. Farr eds., *Aptitude, learning and instructions: III. Conative and affective process analyses* (pp. 223–253). Hillsdale, New Jersey: Erlbaum

Middleton, T. (ed.) (1992). *Virtual Worlds: Real Challenges*. Westport: Meckler Publishing.

Middleton, T., & Boman, D. (1994). *"Simon Says": Using speech to perform tasks in virtual environments*. Presented at the second annual conference on Virtual Reality and Persons with Disabilities. San Francisco.

Minstrell, J. (1988). Teachers' assistants: What could technology make feasible? in Nickerson, R. S. & Zodhiates, P. P. eds., *Technology in education: Looking toward 2020.* Hillsdale: Lawrence Erlbaum Associates.

Moshell, J. M, & Hughes, C. E. (1994). Shared virtual worlds for education. *Virtual Reality World* 2(1): 63–74.

Moshell, J. M., Blau, B. S., Knerr, B., Lampton, D. R., & Bliss, J. P. (1993). A research testbed for virtual environment training applications. In VRAIS '93 Proceedings of the IEEE Virtual Reality Annual International Symposium (pp. 83–89). Seattle, Washington.

Neisser, U. (1987). A sense of where you are: functions of the spatial module, in P. Ellen & C. Thinus-Blanc eds., Cognitive Processes and Spatial Orientation in Animal and Man. Volume II. *Neurophysiology and Developmental Aspects* (pp. 293–310). Boston: Martinus Nijhoff.

Nickerson, R. S. & Zodhiates, P. P. (1988). *Technology in education: Looking toward 2020.* Hillsdale: Lawrence Erlbaum Associates.

Pantelidis, V. S. (1993). Virtual Reality in the Classroom. *Educational Technology* 33 no. 4 (April): 23–27.

Pausch, R., Shackelford, A., & Proffitt, D. (1993). *A user study comparing head-mounted and stationary displays*. In Proceedings of the IEEE Symposium on Research Frontiers in Virtual Reality, San Jose, CA. October.

Pimentel & Teixeira (1992). *Through the Looking Glass*. Intel or Blue Ridge Summit, PA: Windcrest/McGraw-Hill.

Psotka, J. (1993). *Factors Affecting the Location of Virtual Egocenters: From the Renaissance to Cyberspace*. Proceedings of the Third Annual Conference on Cyberspace, Austin, TX, May.

Psotka, J. & Calvert, S. (1994). Measuring heartrate reduces the experience of immersion in VR. In preparation.

Psotka, J. & Davison, S. A. (1993). *Cognitive Factors Associated with Immersion in Virtual Environments*. In Proceedings of the 1993 Conference on Intelligent Computer Aided Training and Virtual Environment Technology, Houston, TX, May.

Psotka, J., Davison, S. A., & Lewis, S.A. (1993). Exploring immersion in virtual space. *Virtual Reality Systems* 1(2): 70–92.

Psotka, J. & Lewis, S. A. Effects of Field of View on judgements of Self-Location. In Preparation.

Psotka, J., Massey, L. D., & Mutter, S. A. (1988). *Intelligent Tutoring Systems: Lessons Learned.* Hillsdale: Lawrence Erlbaum Associates.

Regian, J. W., Shebilske, W., & Monk, J. (1992). A preliminary empirical evaluation of virtual reality as an instructional medium for visual-spatial tasks. *Journal of Communication* 42(4): 136–149.

Regian, J. W., Shebilske, W., & Monk, J. (1993). *VR as a Training Tool: Transfer Effects.* Unpublished manuscript. Armstrong Laboratory, Brooks Air Force Base, Texas.

Rheingold, H. (1991). *Virtual Reality.* New York: Summit.

Rousseau, D. (1993). 3-D Displays and controls for sonar operators. *Virtual Reality Systems* 1(2): 28–32.

Rushton, S. & Wann, J. (1993). *Problems in perception and action in Virtual Worlds.* In Virtual Reality '93: Proceedings of the Third Annual Conference on Virtual Reality. Westport, CT: Meckler Ltd. pp. 43 – 55.

Salamon, G., Perkins, D. N., & Globerson, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. *Educational Researcher* 20(3): 2–9.

Schlager, M. S., Boman, D., Piantanida, T, & Stephenson, R. (1992). *Forecasting the impact of virtual environment technology on maintenance training.* Paper presented at the Space Operations, Applications, and Research Symposium, Aug. 4–6, Houston, TX: NASA JSC.

Sebrechts, M. M., Psotka,J., & Knott, B. A. (1994). Cognitive Tracking. In preparation.

Sheridan, T. B (1992). Musings on telepresence and virtual presence, in T. Middleton, ed., *Virtual Worlds: Real Challenges* (pp. 55–65). Westport: Meckler Publishing,

Slater, M. & Usoh, M. (1993). The influence of a virtual body on presence in immersive virtual environments, *in Virtual Reality '93: Proceedings of the Third Annual Conference on Virtual Reality* (pp. 34–42). Westport, CT: Meckler Ltd.

Sollenberger, Randy L., & Milgram, P. (1991). *A comparative study of rotational and stereoscopic computer graphic depth cues* (pp. 1452–1456). Proceedings of the Human Factors Society 35th Annual Meeting, San Francisco.

Thorisson, K. R. (1993). *Dialogue control in social interface agents* (pp. 139–140). Proceedings of INTERCHI. Amsterdam

Turkle, S. (1993). *Constructions and reconstructions of the self in virtual reality.* Proceedings of the Third Annual Cyberspace Conference, Austin, TX, May.

Varner, D. (1993). *Olfaction and VR.* In Proceedings of the 1993 Conference on Intelligent Computer-Aided Training and Virtual Environment Technology, Houston, TX, May 1993.

Vygotsky, L. S. (1978). *Mind in Society: The development of higher psychological processes.* Cambridge, MA: Harvard University Pres.

VRAIS '93 (1993). Proceedings of the IEEE Virtual Reality Annual International Symposium. Seattle, Washington.

Ware, C., Kevin W. A., & Kellogg S. B. (1993). *Fish tank virtual reality.* Proceedings of INTERCHI '93 Conference on Human Factors in Computing Systems (pp. 149–160). Amsterdam.

Warner,H.D., Serfoss, G. L., & Hubbard, D. C. (1993). *Effects of Area of Interest display characteristics on visual search performance and head movements in simulated low level flight.* Armstrong Laboratory Technical Report. 1993-0023.

Wertheim, A.H. & Mesland, B. (1993). *Motion Perception During Linear Ego-Motion.* Institute for Perception Technical Report IZF-1993–3, TNO Institute for Perception, Soesterberg, The Netherlands.

Wexelblat, A. (Ed.). (1993). *Virtual Reality Applications and Explorations.* Toronto: Academic Press Professional.

Wolpert, L. (1990). Field-of-view information for self-motion perception, in Warren, R. & Wertheim, A.H. eds., *Perception and Control of Self-Motion* (pp. 101–126). Hillsdale New Jersey: Lawrence Erlbaum.