BRUCE W. HAMILL

IMMERSING PEOPLE IN VIRTUAL ENVIRONMENTS: PERCEPTUAL AND COGNITIVE CONSIDERATIONS

In virtual environment systems, people are immersed in realistic three-dimensional computer simulations of real-world spaces for a variety of entertaining and productive purposes. The use of these systems raises fundamental questions about how to enhance the users' perceptual and cognitive performance and overcome their limitations as they interact with the technology. The focus here is on psychologically important features of the technology, considerations that affect the perceptual and cognitive quality of immersive involvement and human performance, and the kinds of tasks for which virtual environment technology might be especially beneficial.

INTRODUCTION

Virtual environment (VE) technology is highly immersive, requiring the human user to become subjectively and even spatially involved in an enveloping simulation of reality. The premise of VE seems to be to enhance the interaction between people and their systems by taking advantage of the natural perceptual and cognitive abilities of people in technologically sophisticated, realistic, simulated settings—virtual reality. It thus becomes very important to understand how people perceive and interpret events in their environments, both in and out of virtual representations of reality. We must address issues of human performance to understand how to develop and implement VE technology that people can use comfortably and effectively.

Research and development on various guises of VE technology, including artificial reality,[1] virtual reality,[2–6] and virtual environments,[7] have resulted in some spectacular technology embodying impressive advances in computer system hardware and software and in peripheral devices used with such systems. Moreover, commercial VE systems are becoming increasingly available. However, little research has been conducted concerning human performance issues in the context of the new and proliferating technologies. Fundamental questions remain about how people interact with the systems, in what kinds of tasks they may be most appropriate and effective, how they may be used to enhance and augment cognitive performance in such environments, and how they can best be employed for instruction, training, and other people-oriented applications.

Three aspects of human perceptual and cognitive performance in VE's are considered here. The first involves characterizing VE's in terms of features important from a psychological perspective. The second concerns perceptual and cognitive considerations that enable, enhance, and limit immersive involvement and human performance in VE's. The third identifies some kinds of tasks for which VE technology might be especially useful in the light of human perceptual and cognitive performance considerations.

PSYCHOLOGICAL FEATURES

One of the earliest examples of virtual reality was Morton Heilig's Sensorama, an entertainment device that provided the user with a three-dimensional (3D) movie accompanied by appropriate sounds, odors, and even wind.[8] Few, if any, of today's VE's include effects for all those senses, although they are certainly technologically feasible. In particular, virtual auditory space is an active area of research.[9] Acoustic technology can now simulate 3D space through headphones, permitting 3D auditory localization of sounds presented in VE's. Listeners using virtual acoustic displays that appropriately model head-related transfer functions can obtain useful and accurate directional localization information.[10] This capability is useful for directional signaling, pointing out objects or features of the environment, and orienting the user. It might be effectively used for multiperson communications, such as virtual meetings, shipboard intercoms, and radio net monitoring, by localizing each speaker or channel in a virtual space. Tactile, vestibular, and kinesthetic feedback are also candidates for VE implementation.

One of the defining features of VE's is a sense of immersion in the target environment being simulated and presented through displays. Although we use the term "immersion" here to specify conditions of user interaction with VE technology, the term has also been used by others in reference to subjective responses to using VE's.[11] The user of the technology becomes subjectively, and sometimes also spatially, immersed in a VE in which simulated objects exist and events occur. These conditions are depicted in Figure 1. Once immersed in a VE, one has an egocentric world view. The environment exists for the user, as well as around the user in spatial imersion, and it is up to the user to initiate interactions with the environment. Different kinds of VE technology support the different modes of interaction.

One may move through virtual space by various means, depending on the particular technology involved. Some technologies permit one to move by pseudomotion, such as "flying," whereby only visual feedback is available.

Other technologies also permit locomotion, resulting in attendant sensory (visual, kinesthetic, and perhaps auditory) feedback. All of the technologies use sensory illusion to achieve their immersive effects and the attendant sense of being able to move through a simulated environment.

Subjective Immersion

One kind of VE technology employs subjective immersion, in which the user interacts as if using an ordinary desktop computer system. The user views the system from the usual close but remote position and interacts through standard or special-purpose input or control devices such as keyboards, mouse controls, trackballs, joysticks, or force balls. The user can fly or otherwise move around in a two-dimensional (2D) representation of 3D space. Three dimensions are represented on 2D displays through the use of simulation software employing perspective, object rotation, object interposition, relative size, shading, motion, and other effective visual cues appropriate to the task at hand.

In subjective immersion, one interacts with the simulation by changing the viewing perspective, or moving around and into the 3D virtual space via facilities provided by the simulation program. Ordinarily, the computer's keyboard or mouse is used to move in two dimensions, as well as into and out of the display's apparent depth. One might, for example, "drive" into a simulated countryside along a road receding into the perceived distance, passing by trees and buildings that appear along the way, by holding a cursor on a particular target object in the perceived distance; the simulation would provide ways to control direction and speed of travel.

Effective subjective immersion gives one the sense of being there, interacting directly with the simulated environment and the objects and events in it, despite being physically remote from the virtual space. Consider, for example, how effectively 2D displays such as video games, television programs, and movies subjectively involve, or immerse, their respective players and audiences. The effectiveness of subjective immersion depends upon how engaging the simulated 3D environment can be made on the 2D display and how easy it is to control the interaction with available input or control devices. It also depends upon how the environment is designed and how well it is designed to shape the potential interactive experiences available to the user and to make them interesting.[12]

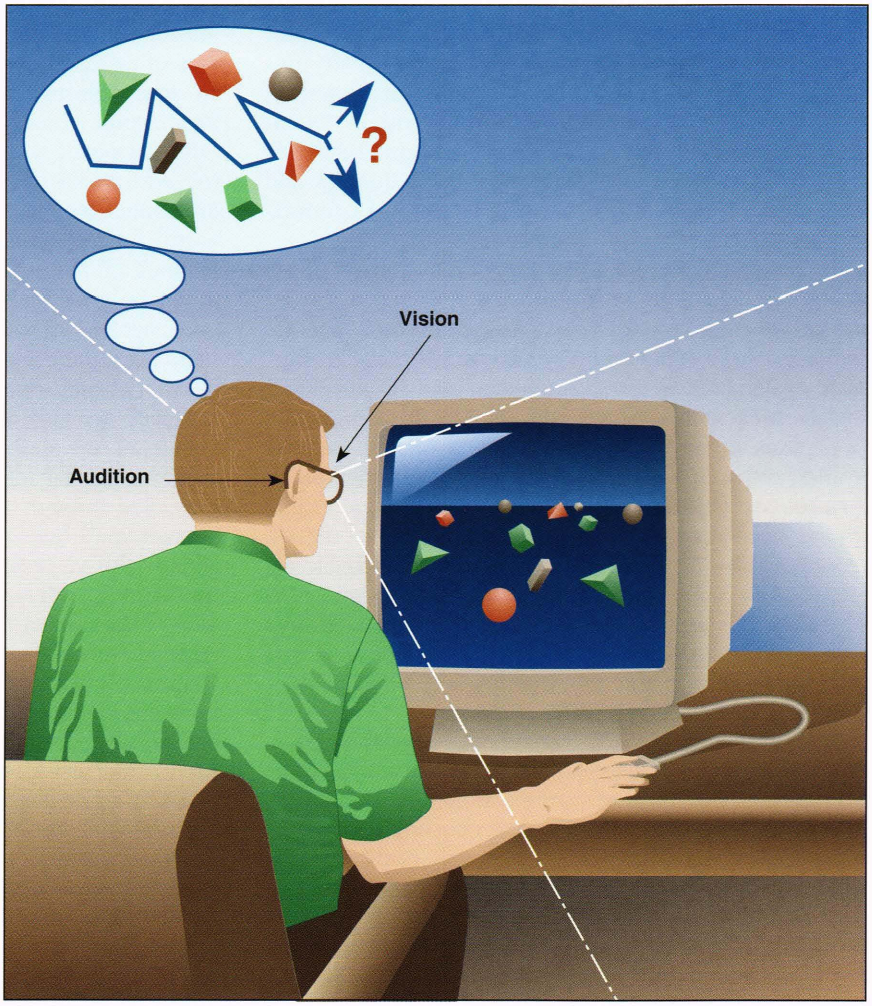


Figure 1. Cartoons depict subjective immersion (this page) and spatial immersion (opposite page) versions of the same virtual environment task. In both examples the user is shown attempting to navigate through a space littered with recognizable objects. In the subjective immersion setting, the user views a computer-based 2D or pseudo-3D display, moving through the environment via a manually operated control device. Feedback to the user is through visual cues and (perhaps) auditory cues. In the spatial immersion setting, the user views a 3D scene presented in a sensor-laden helmet-mounted display that responds to changes in head orientation and whole-body location by changing the view being presented. Feedback is through visual and kinesthetic cues related to head movements and may also include localized (or nonlocalized) auditory cues, real or simulated touch, and kinesthetic cues from hands, arms, feet, and legs in systems allowing whole-body traversal of the space. Sight lines indicate what the user sees. Cognitive similarities and differences between subjective and spatial immersion in tasks like navigating along an imaginary path among objects (see thought bubbles) have theoretical and practical implications.

Spatial Immersion

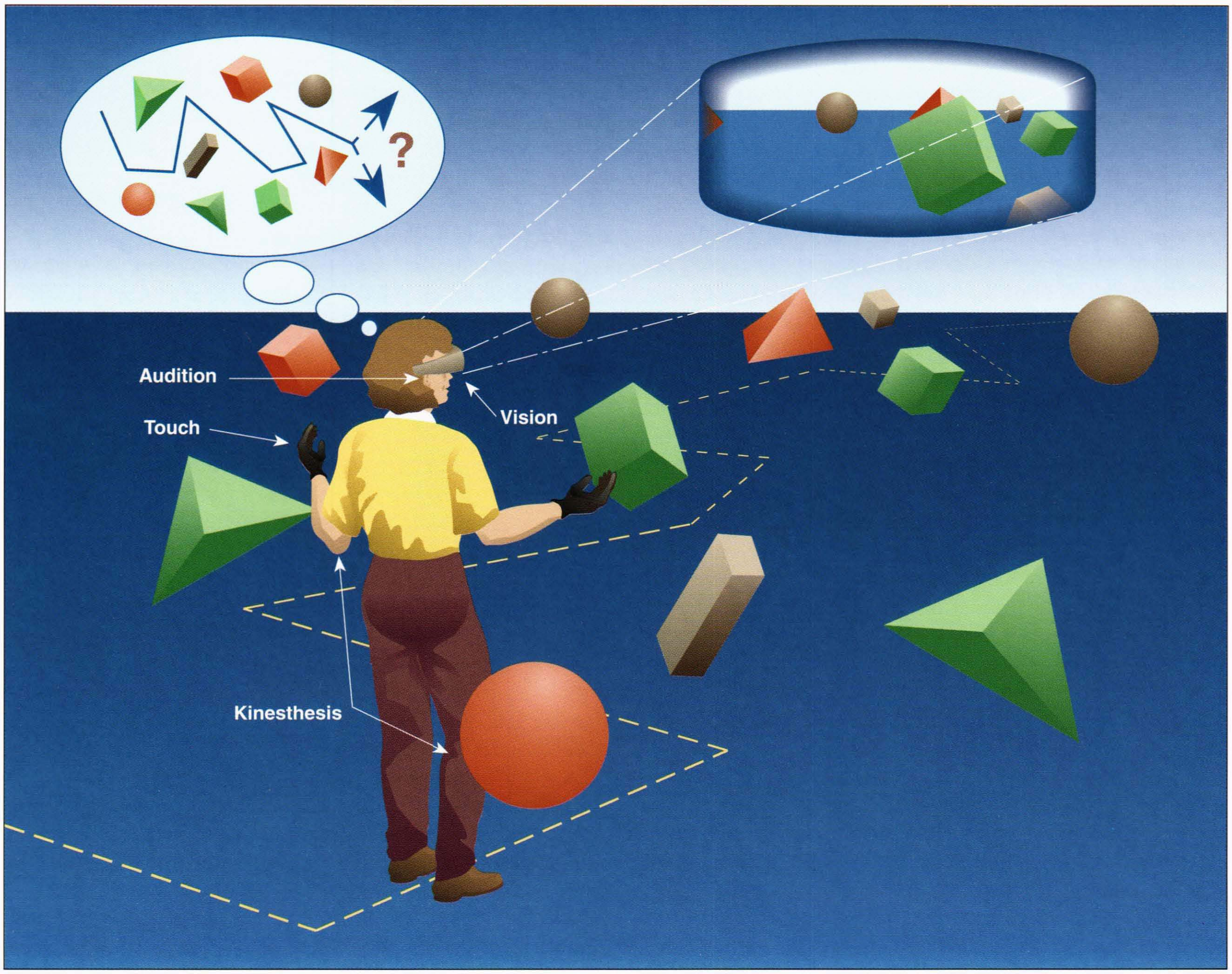
The other kind of VE technology uses spatial immersion. The user is required to get inside the virtual space by wearing special equipment, typically at least a helmet-mounted display that bears sensors to determine precise helmet position within the VE system's range, in order to interact with the simulated environment. The user is thus immersed in a quasi-3D virtual space in which objects of interest appear to exist and events occur above, below, and around in all directions toward which the user turns his or her head. One has the sense of being *in* there, rather than just being there, as with subjective immersion.

Visual images presented to the user on a helmet-mounted display may be presented stereoscopically or by other means that can enhance the sense of reality of the 3D virtual space. Depending on the particular technology, one can view the surrounding environment from a stationary position by turning one's head, whereby displayed objects and scenes follow head movements and direction of gaze, or one can look around and move within the VE, whereby displayed objects and scenes follow not only head movements and direction of gaze, but also actual traversal of some physical space associated with the VE. In some systems, the user can also interact with virtual objects in the environment by reaching out with a hand and pointing at or even manipulating the objects.

HUMAN PERFORMANCE CONSIDERATIONS

The distinctions between subjective and spatial immersion are related to the issue of simulation fidelity and to the compatibility principle (to be discussed later), both of which are important to the design of VE's used in support of human task performance. The degree of fidelity required in a VE simulation to support performance may differ as a function of the kinds of tasks involved. For instance, a relatively high degree of fidelity may be needed in aviation simulation for training, where it is important to simulate the spatial layout of physical objects in the real environment, but it may not be necessary in other task domains. In fact, the concept of fidelity may not even apply in some domains, as in representations of abstract environments such as complex data sets or the structure of a computer's file system, where some new measures of appropriateness are needed.

Virtual environments based upon or including representations of abstract entities require special attention to human performance considerations. In such environments, the concept of representation or simulation of



reality may be a difficult one to implement: What, after all, is the reality of an abstraction? For example, what does it mean to represent or simulate a computer's file system or a tactical situation assessment? What are the critical elements of the representation from the perspective of the VE user? The answers to these questions depend upon how users think about problems and what they have to accomplish through interaction with the system. Knowledge about how people think about solving problems in such domains should drive the design of system elements and the manner in which they are represented and simulated for viewing, hearing, or sensing. The way people think about abstractions represented in VE systems, however, may differ significantly from the way they think about those abstractions under ordinary circumstances. The VE representation could even distort the way they think about the abstractions and thereby influence, positively or negatively, the effectiveness with which they employ the VE system.

It may be desirable to create certain kinds of distortions that will permit users to comprehend a representation of a constructed reality that might otherwise not be feasibly represented. Doing so amounts to imposing designed abstractions on users through which to facilitate interpretation of large or complex real-problem spaces. For example, air traffic controllers and watch standers at ship command information centers need environments that represent movements of aircraft through a half million cubic miles of airspace. In these environments, distances might need to be represented on different scales and on different axes for various purposes, and aircraft sizes on such representations would not be realistic. Nevertheless, the environments would be effective to the extent that the designed abstractions could relate evolving situations to familiar views of the problem space and facilitate users' abilities to interpret and assess situations arising in airspaces of such magnitude. In addition to designing appropriate abstractions for such purposes, means for assuring the effectiveness of their implementation in subjectively and spatially immersive VE's would need to be determined.

To make the best use of VE technology, we need to learn more about what kinds of cognitive tasks can benefit from spatial immersion, what kinds of tasks do not require spatial immersion but can benefit from subjective immersion, and what kinds of tasks may be unaffected or even adversely affected by VE's. There may be different learning and performance consequences of using one or the other kind of VE simulation. If so, the consequences would have important implications for the design of training systems and other applications of VE technology in support of task performance.

Considerations such as those just described suggest that a psychological sense of immersion is a major feature of VE's; that is, a qualitative, subjective sense of involvement in the displayed environment seems to be essential to the effectiveness of any VE. How is this sense of involvement or immersion achieved through the user's perceptual and cognitive processes?

Many questions arise in analyzing human perceptual and cognitive performance in VE's. Does the human mind have a natural propensity to perceive a VE as an adequate representation of reality, just as it has a natural propensity to perceive three-dimensionality and objects in artificial visual scenes on the basis of minimal perceptual cues? What governs whether spatial immersion is desirable for supporting task performance, or whether subjective immersion is sufficient? What determines the perceptual–cognitive adequacy of the realism provided by a VE? How can proper levels of simulation fidelity be specified and assured for particular applications? Theories, methods, and data from psychology, cognitive science, and artificial intelligence in regard to visual displays, visualization, visual–spatial cognition, navigation, cognitive maps, spatial orientation, reasoning, learning, and compatibility are relevant and important considerations in answering such questions.

Visual Displays

Perceptual and cognitive distinctions between VE displays and other kinds of displays relate to the kinds of tasks for which the technology is used. We are accustomed to watching television and using textual and graphic computer-based displays, such as those driven by desktop computers in various kinds of everyday tasks. But computer-based displays are often just 2D electronic versions of familiar paper-based texts, pictures, and graphics. Some are dynamic, of course, allowing the viewer to see changes occurring through time. This is a satisfactory way to perform the kinds of tasks for which paper-based presentation once sufficed.

Recent developments in technology have produced several means of generating 3D displays. Since the visual system has a natural propensity to interpret displays and scenes as three-dimensional, 3D displays may permit more efficient use of our visual apparatus for information extraction than can be achieved with 2D displays.

How do familiar kinds of 2D and 3D displays relate to VE applications? What is it that defines VE's as distinct from the more familiar kinds of display technology? As indicated previously, one can get cognitively and emotionally involved even in 2D displays. But is that enough to constitute immersion in a VE?

Recent research on the design and testing of visual displays has begun to take account of the cognitive task requirements to be supported by computer system displays.[13] Although more work is needed in elaborating the nature of the cognitive requirements so that more effective design and testing can be accomplished, the empirical approach represented by such research is also appropriate to the design and testing of VE's intended for use in different contexts. For work of that kind to proceed, we need to make better use of our understanding of the perceptual and cognitive structures and processes with which users interact with VE's. Some of the most relevant ones are discussed in sections that follow.

Virtual environments offer new opportunities for going beyond traditional ideas about human–system interaction by enabling the user to move around inside a data or information set, rather than just viewing it remotely. Although this feature may increase the potential for user interaction with data, it may also introduce unforeseen problems and difficulties in how users find their way around in VE's to accomplish their intellectual tasks. Further, the different technologies available to implement this interaction have features that may make one or another of them preferable, depending on how the system supports the various kinds of perceptual and cognitive tasks.

The limitations of subjectively immersive VE's make them inadequate for some uses, for example, where a user would benefit from being spatially engulfed in the simulation to take advantage of positional and relational features inherent in that type of environment. Some potentially useful applications involve the immersion of the user in 3D space where means are provided for maneuvering through that space. One example is pilot training in which the displays and controls of a cockpit are spatially simulated. Another is architectural design, in which detailed construction plans can be used to create virtual structures that permit designers to enter, move around in, and visualize their designs and how they relate to one another before they are actually built.

Visualization

Visualization researchers have devised interesting ways for computer users to manage and present large data and information sets. The viewing format makes interpretation of the displays relatively intuitive, relying on natural structures in human vision and cognition for effortless analysis.[14–16]

Representations have been developed for several kinds of information structures, such as the Information Visualizer workspace, the Perspective Wall for relating detail to context (Fig. 2), and animated 3D hierarchical Cone Trees (Fig. 3).[17] Other visualization examples include SemNet, which supports 3D graphic representations of large knowledge bases,[18] a system for 3D display of medical data,[19] and Tree-Maps, a space-filling depiction of hierarchical information structures such as collections of computer files.[20] With some of the systems, the users can determine at a glance what they want to know about the data or information set being interrogated.

Although the display formats were developed to facilitate interpretation of complex data and information through computer graphics and visualization techniques, they were not necessarily designed as VE's. To the extent that one can interactively traverse the abstract spaces that they depict, however, they might be considered subjectively immersive VE's. Whether spatial immersion would improve a user's interaction with and understanding of the representations of abstract information is an open question.

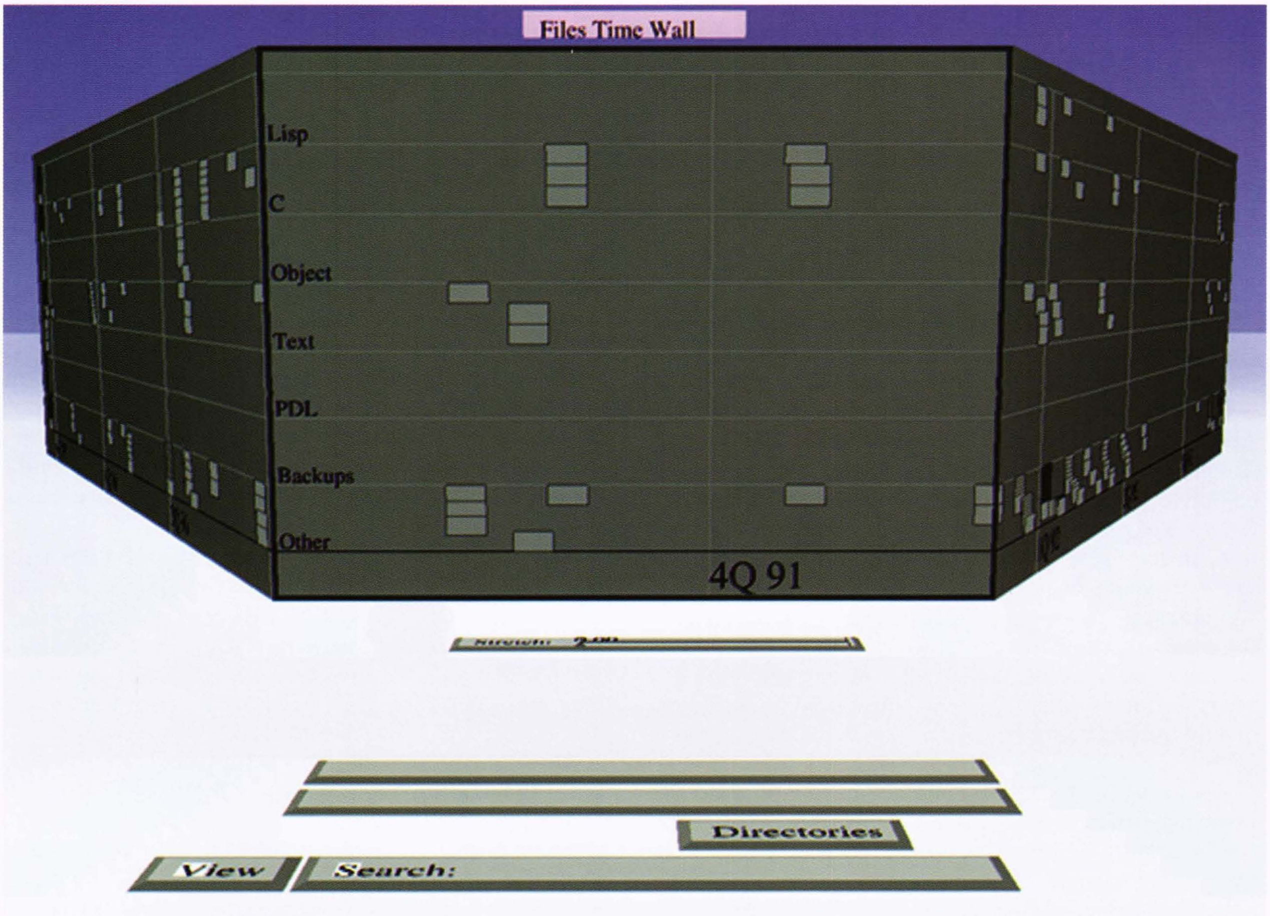


Figure 2. The Perspective Wall offers a means for visualizing linear information in context for interactive viewing and searching. The center panel presents 2D information detail and permits horizontal and vertical structuring, such as layering. The side panels show less detail but provide context and 3D perspective. (Reprinted, with permission, from Ref. 17, p. 69, © 1993 by the Association for Computing Machinery.)

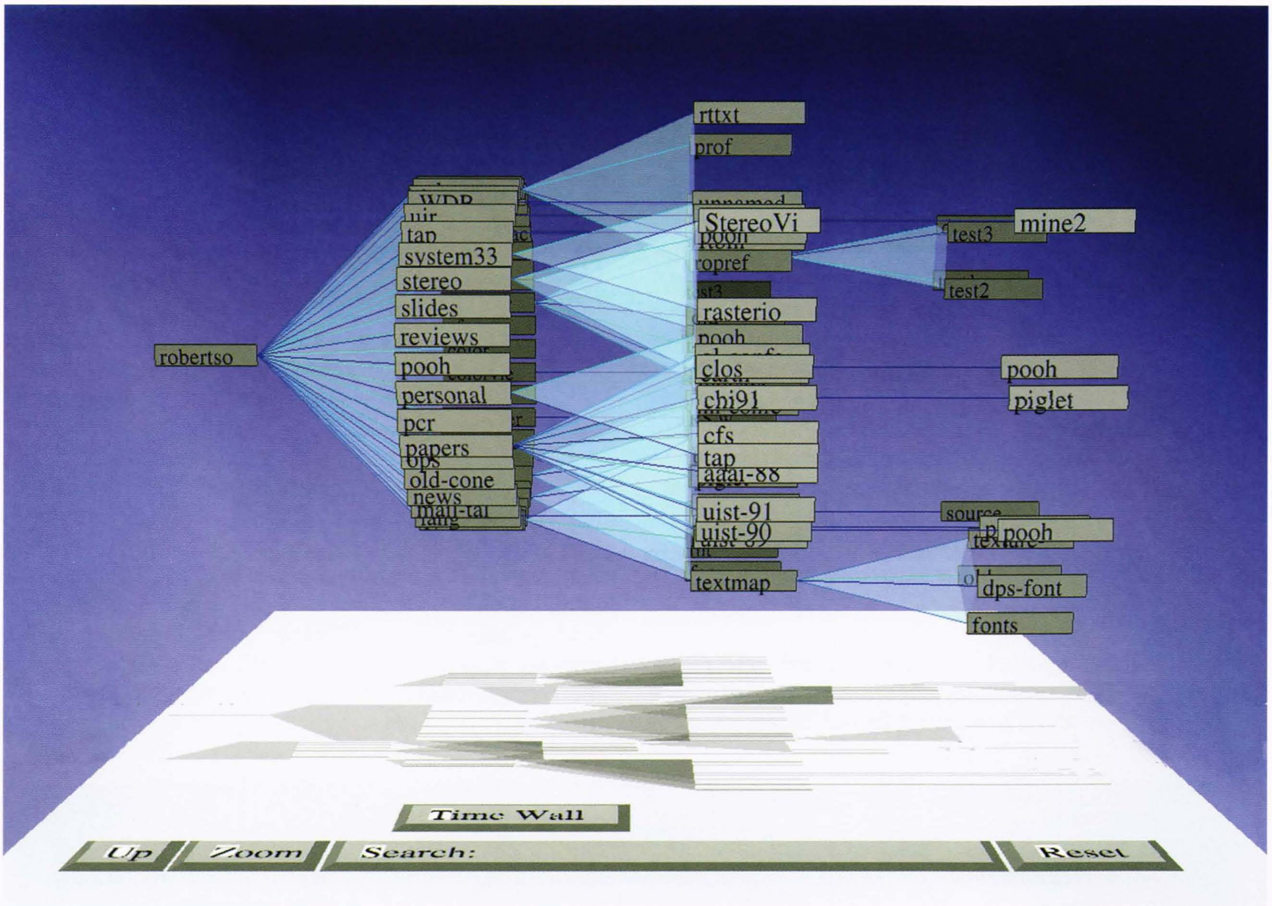


Figure 3. Cone Trees facilitate the visualization of hierarchical information sets. Trees can be displayed in vertical or horizontal orientations and can be rotated in depth. The user can focus on different parts of trees and prune, grow, and move them interactively. (Reprinted, with permission, from Ref. 17, p. 67, © 1993 by the Association for Computing Machinery.)

Visual Cognition

Research on visual cognition provides a starting point for understanding how people interact with VE's. The design of VE's relies heavily on the ability of users to extract relevant information from real-world scenes and from visual displays, and to traverse real-world spaces.

Visual cognition includes knowledge structures and cognitive processes that relate visual inputs to interpretations and other conceptual uses of displayed information. In the VE setting, visual cognition is used in navigating through displayed spaces and finding, identifying, and acting upon virtual objects of interest. User interactions are supported by the VE system's representations of data and information and by the means provided for accessing them. Interactions are successful to the extent that the system's features map readily to the user's knowledge and expectations.

Recent work in cognitive science has highlighted the importance of devising representations appropriate to the user's task. Examples are a special-purpose architecture that permits imagery to be mapped into discrete symbolic representations, and research findings on reasoning with diagrams.[21]

Diagrams are important visual aids to reasoning because they provide directly interpretable depictions of information about problems to be solved, at least to those who have learned to use them.[22,23] Graphs are a ubiquitous means of depicting data. Nevertheless, the design of useful and easily interpreted graphs remains an art form, although graph design is an active area of research.[24,25] The design of subjectively and spatially immersive VE's that include depictions of abstract information might benefit from knowledge of how to design and use diagrams and graphs.

An important perceptual–cognitive consideration in the design and use of VE technology is how people navigate and remain oriented in simulated environments. When users are immersed either subjectively or spatially in a simulated world, they must be able to determine where they are, where they have been, where they want to go, and how to get from here to there.

Three important requirements for using VE's effectively for problem solving and for training are (1) being able to navigate appropriately within the virtual spaces depicted in VE displays, (2) being able to reason appropriately about the virtual objects and about the spatial or otherwise abstract concepts represented in VE simulations, and (3) being able to learn, that is, to acquire knowledge and skills, in the VE and to transfer what is learned to an external target domain.

Navigation

One might expect the ability of people to navigate in virtual space to be analogous to, or at least closely related to, their ability to navigate in real space. One must consider, however, that a person's ability to navigate locally around furniture and other objects in a real room may be qualitatively different from how that person navigates through extended spaces such as unfamiliar real neighborhoods, which, in turn, may not be indicative of how the person would navigate through local and extended abstract spaces in VE's. As exemplified by the effort required in using mnemonic techniques such as linking ordered parts of an oration to mental stops along a path through imagined rooms of a familiar building, navigation through imaginary spaces such as VE's may require specialized instruction and considerable experience before it can be performed effectively. (Of course, learning to navigate in real spaces also benefits from instruction and experience.)

What considerations influence how people find their way around in VE's, what kinds of landmarks and signposts they use, and how they establish relationships among objects in virtual space? Studies of the organization of human memory, the structure of cognitive maps, and the nature of spatial abilities provide some insight into these issues, but how people navigate and remain oriented in simulated environments has not been the focus of much research. What has been done suggests that users need landmarks, signposts, and anchors related to familiar objects and places, even metaphorical ones, to navigate effectively through virtual space.

Spatial Cognition

What people know about space and how to interact with it influences their interpretations of spatial representations in visual displays and their performance of spatial tasks.[26-28] For example, perceptual context and other considerations affecting how one interacts with spatial events can influence memory for those events, memory structures and representations, and how such structures and representations can be measured and modeled.[29,30]

Spatial reasoning is supported by achieving appropriate mappings between problem portrayal and interpretability of that portrayal by problem solvers. Thus, the selection of a spatial representation presents important challenges for system designers. In particular, they should take into account the kinds of spatial reasoning to be supported and spatial relations important to spatial interpretation and reasoning.[31,32]

Cognitive Maps

In one of the earliest scientific publications on cognitive maps, Trowbridge reported a study of differences in methods of orientation and sense of direction used by "civilized man" (the "ego-centric method" based on knowledge of the points of the compass) and those used "not only by birds, beasts, fish, insects, etc., but also, in all probability, by young children and by a large proportion of mankind living in an uncivilized state" (the "domicentric method" based only on knowledge of regions traversed). Trowbridge estimated that "the proportion of people who have so-called 'imaginary maps' is astonishingly large, being of the order of thirty to fifty per cent., if not a much higher ratio; hence the matter is one of general interest."[33]

Considerable recent work on cognitive maps is relevant to understanding how people interact with VE's. Some of the main issues concerning cognitive maps include mental structures and representations of geographical areas, reference systems, learning and memory, and inferential use of cognitive maps.[34-36]

Spatial Orientation and Navigation

Long after Trowbridge's report, orientation and sense of direction in the real world remain important research areas. In addition, studies of navigation in the real world have provided further insight into issues that may be extended metaphorically to computer-based system displays and to VE's, including environmental learning through navigation, memory for routes, searching for objects in multidimensional space, estimation and representation of distance information, and alternatives to traditional models of seafaring navigation.[37-39] For example, some surprising differences in spatial orientation and distance estimation performance were observed in an experiment in which walking through physical spaces was compared with traversal of virtual representations of those same physical spaces in VE's characterized by subjective immersion and two levels of spatial immersion. In particular, although accurate distance estimates were made by those subjects walking through physical spaces, the same distances represented in the VE's were consistently underestimated, and the most immersive condition yielded the greatest underestimation.[40] Although the exact sources of the observed effects remain to be specifically identified, the results clearly suggest a need to consider navigation performance in VE design.

The literature provides evidence of the importance of visual and spatial memory, spatial orientation ability, and knowledge of spatial configurations, landmarks, and routes in spatial exploration, all of which are fundamental to the effective use of VE's, even for simple tasks.

Reasoning

Since reasoning, by its very nature, involves applying structured knowledge and procedures to solve problems, it might be expected that principles and processes of spatial and abstract reasoning in VE's are essentially identical to those of spatial and abstract reasoning under ordinary conditions. Thus, one would expect not only to be able to recognize or identify objects in VE's, but also to be able to discern what can be done with them, since visible features of real objects serve as cues to possible actions that those features afford and uses to which objects can be put. For instance, upon seeing a virtual object of appropriate apparent size and shape with a handle on it, one might expect to be able to pick it up by the handle and turn, tip, or carry it as one would a real object with those characteristics, because handles afford those kinds of actions.[41] Depicting such features in ways that support appropriate reasoning about the purposes and potential uses of virtual objects and depicted abstractions is an important VE design consideration.

Fundamental differences may exist, however, in the nature of reasoning between VE's and real environments. We need to determine whether such differences exist and what their effects might be. Understanding how people reason about spatial relationships among objects and structures in virtual space, and about abstractions based on them, is crucial to the design of VE systems.

Learning

Finally, how people learn in VE's, how well they learn, and how well what is learned transfers to other domains are not yet well understood. On the basis of the ostensible success of flight simulators and other simulation-based training systems, one might expect that the introduction of VE's would enhance such systems. The use of VE's would seem to be highly appropriate for pilot training in a virtual cockpit, since a spatially immersive VE might be expected to improve transfer of training to an analogous real cockpit space (there is high face validity, as well as content validity, for the use of VE's).[42,43] The basis for transfer of training from spatially immersive VE's to other domains that are not so spatially oriented is less obvious (there is less face validity, and perhaps less content validity, for VE use). In those domains, it may be that features of VE's are different enough from the more familiar simulation-based training systems to require people to develop new abilities to learn and to transfer what they learn to target applications.

Compatibility

The human performance principle of compatibility in display and system design holds that successful information transfer should be maximized under conditions in which information recoding effort by users is minimized.[44,45] Thus, users interacting with information displays of various kinds should find it easier to work with interfaces designed to minimize the recoding effort. Not surprisingly, some effort on the part of the user is necessary for effective information transfer to occur, even with the best-designed interfaces; compatibility by itself is not enough.[46] Nevertheless, compatibility between users' expectations and features provided by VE systems may be an important aspect of how well users can employ the systems. For example, a concrete spatial navigation task such as following a route among buildings in a spatially immersive environment might be considered a high-compatibility combination, whereas an abstract navigation task such as finding items in a data set in the same kind of environment might be a low-compatibility combination.

Qualitative differences in cognitive problem-solving performance may result from being in there (using spatially immersive VE's) versus being there (using non-spatially-immersive VE's). Such differences may arise in part as a result of compatibility effects between types of problem representations and VE features.

In VE's, as in other kinds of complex computer-based simulation settings used for instruction and training, it is important to understand the relationships among the learner, the knowledge domain in which tasks are performed, techniques of information presentation, and features of the simulation system.[47-49]

A related issue is the cost-effectiveness of using VE technology for various purposes. For instance, since spatially immersive VE technology is more complex and expensive than subjectively immersive VE technology, it may be cost-effective to use spatial immersion for teaching pilots or drivers how to operate controls and respond to displayed situations in inherently spatial domains, but not as cost-effective to use such environments for teaching people how to solve database problems or to diagnose system failures or medical problems. Questions of cost-effectiveness cannot be adequately answered until we have human performance data that we can analyze.

Simulator sickness has arisen with simulators having certain physical characteristics that can trigger adverse physiological effects.[50] For example, temporal mismatches between presented and expected visual displays can be disorienting. Video images presented in synchrony with the viewer's alpha rhythm can produce headache, and mismatches between sensory and vestibular inputs to the user can produce nausea.

It remains to be determined how VE technology might be used to support abstract tasks, such as database navigation, which are related to, but removed from, the level of VE simulation by metaphorical abstractions. One might suppose that structural parallels between virtual spaces and metaphorically organized data spaces could be defined and exploited through VE technology. Research is needed on this and other aspects of cognitive performance, including the effects of VE's on users' attention and memory processes, spatial and temporal resolution requirements for displays, and effects of training and experience in using VE's on perceptual and cognitive performance and on system usability.

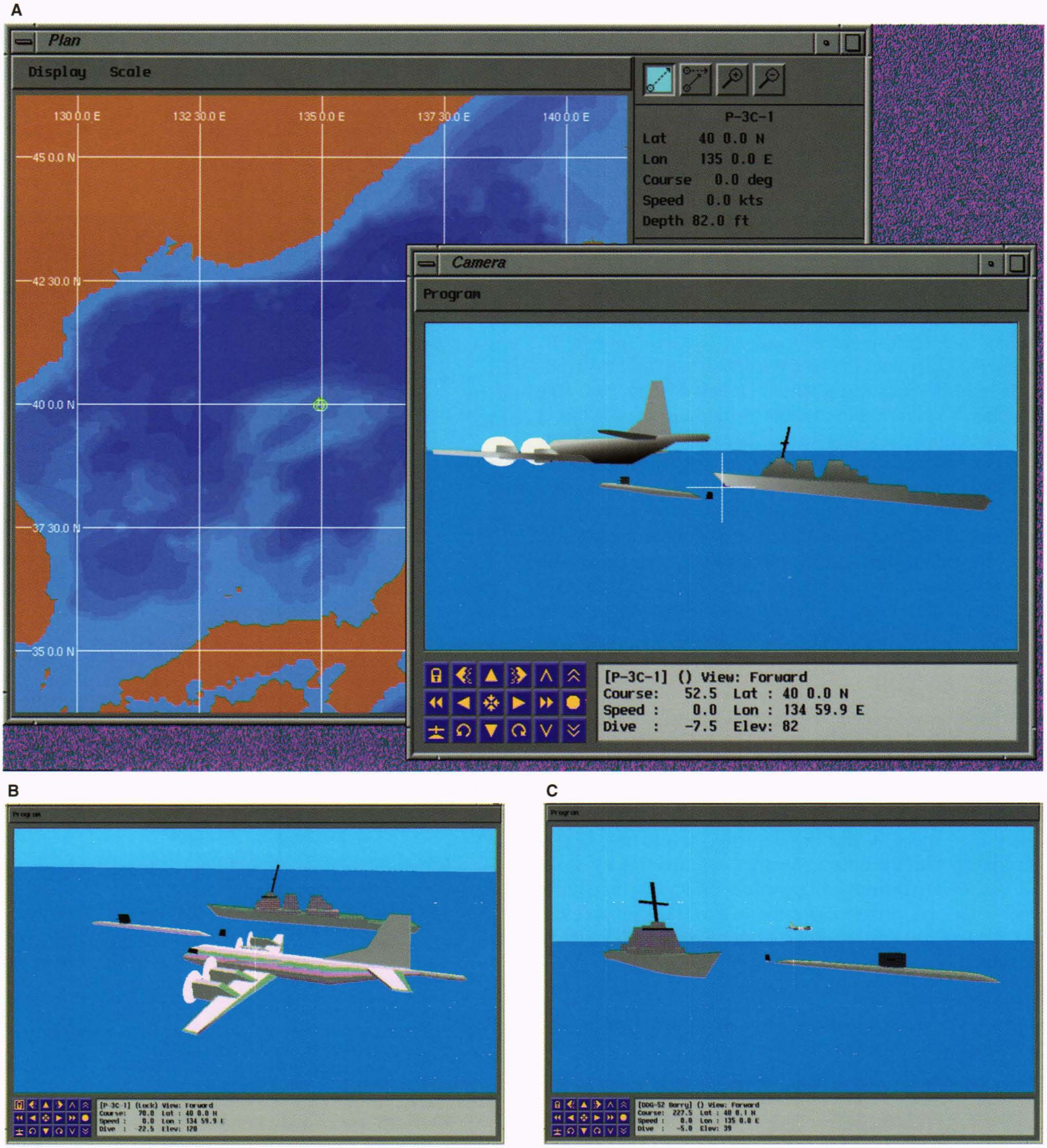
USING VIRTUAL ENVIRONMENTS

Given the features of VE's and an appreciation of perceptual and cognitive considerations that affect how people interact with them, how can we best take advantage of VE technology? As the preceding discussion suggests, this question must be addressed by considering the kinds of uses to which VE's will be put, together with the nature of the tasks that people will be expected to perform in VE's.

One obvious use is for entertainment. Entering and exploring a virtual world is a novel and enjoyable experience. With the user immersed in a 3D space surrounded by directional sound and other sensory feedback, that novelty can be augmented with entertaining or challenging tasks characteristic of games, puzzles, and activities already familiar to video game players. Such experiences offer new tests of people's perception and wits and expand the horizons of current entertainment technology by introducing new dimensions of psychological involvement. Imagine the action possibilities and challenges inside a spatially immersive Jurassic Park!

Virtual environment systems may have important new uses in support of data analysis and interpretation. One task domain that stands to benefit from VE technology is data visualization. Tailoring data requirements to spatially immersive VE's would permit a user or analyst to view a data set in novel ways and to explore the data set by moving through it, viewing it from various perspectives in search of patterns that may not otherwise be apparent. To some extent, some advanced statistical analysis and display packages offer this feature, even for desktop computers, but without spatial immersion. Being able to move around inside a data set may offer new insights, as well as new challenges, for understanding how people identify and interpret patterns in complex data structures.

Another data analysis and interpretation task domain is that of maintaining situation awareness in dynamically changing contexts, such as air traffic control and military operations. Being able to visualize these kinds of situations directly in 3D space offers the potential for more effective prosecution of task requirements having spatial



```
P-3C-1
Lat     40 0.0 N
Lon     135 0.0 E
Course    0.0 deg
Speed    0.0 kts
Depth 82.0 ft
```

```
[P-3C-1] () View: Forward
Course:   52.5  Lat : 40 0.0 N
Speed :    0.0  Lon : 134 59.9 E
Dive  :   -7.5  Elev: 82
```

```
[P-3C-1] (Lock) View: Forward
Course:   70.0  Lat : 40 0.0 N
Speed :    0.0  Lon : 134 59.9 E
Dive  :  -22.5  Elev: 120
```

```
[DDG-52 Barry] () View: Forward
Course:  227.5  Lat : 40 0.1 N
Speed :    0.0  Lon : 135 0.0 E
Dive  :   -5.0  Elev: 39
```

Figure 4. Advanced displays for use in the APL Submarine Combat Information Laboratory. **A.** An interactive, subjectively immersive virtual environment display. This display can be used in conjunction with a bathymetric geographical situation plot and a text window on the same workstation screen to facilitate interpretation of tactical situations. **B.** and **C.** Other virtual environment perspective views of the same situation. (Graphics courtesy of Creighton Donnald, APL Submarine Technology Department.)

features difficult to represent in conventional 2D displays. An example of a submarine navigation display developed for these purposes at APL is shown in Figure 4; see the article by Dennehy, Nesbitt, and Sumey in this issue for an APL air defense example.

Education and training could benefit from those extensions beyond current simulation capabilities that VE technology affords. For example, combining spatial immersion in a 3D virtual space with resized simulations of very small or very large objects would make it possible to explore molecules and galaxies by touring them and viewing them from different perspectives, which, in turn, could facilitate learning about them. One might fly through a virtual engine or other piece of complex equipment to learn how its parts move and interact as part of a maintenance training program. In this example, one might also be able to use virtual tools to practice performing tests and repair tasks on the virtual objects. In addition, novel hybrid displays could be devised, such as head-up displays that would project virtual tools or informative text onto real objects.

Finally, a natural enhancement of VE technology would be the incorporation of increasingly available sophisticated multimodal displays, including still and motion video, audio, and voice input and output, that can furnish the immersed user with interactive capabilities hitherto available only in one's imagination. One day we may be able to enter a VE, navigate through its domain by moving in the directions we want to go, request higher or lower levels of abstraction and greater or less aggregation of information, inspect audiovisual elaborations of domain details, select information for analysis by pointing at regions of interest, speak instructions about analyses to be performed, listen to synthetically spoken or tonally constructed summaries of analyses while viewing multidimensional graphs of results, and order output to be printed or videotaped back at our offices.

CONCLUSION

Virtual environment technology appears to present a new leading edge in the evolution of the science and practice of human-system interaction and integration. It brings us a step closer to achieving technology with which users can interact in intimate symbiosis to accomplish their tasks. Achieving improved levels of task performance with the new technology will require advances in our understanding of people's information requirements for task performance and of how best to represent such information for appropriate perceptual and cognitive assimilation and use.

REFERENCES

[1] Krueger, M. W., *Artificial Reality II*, Addison-Wesley, Reading, Mass. (1991).

[2] Aukstakalnis, S., and Blatner, D., *Silicon Mirage: The Art and Science of Virtual Reality*, Peachpit Press, Berkeley, Calif. (1992).

[3] Helsel, S. K., and Roth, J. P. (eds.), *Virtual Reality: Theory, Practice, and Promise*, Meckler, Westport, Conn. (1991).

[4] Pimentel, K., and Teixeira, K., *Virtual Reality: Through the New Looking Glass*, McGraw-Hill, New York (1993).

[5] Rheingold, H., *Virtual Reality: The Revolutionary Technology of Computer-Generated Artificial Worlds and How It Promises to Transform Society*, Simon and Schuster, New York (1992).

[6] Wexelblat, A. (ed.), *Virtual Reality: Applications and Explorations*, Academic Press, New York (1993).

[7] Fisher, S. S., "Virtual Environments: Personal Simulations and Telepresence," in *Virtual Reality: Theory, Practice, and Promise*, Helsel, S. K., and Roth, J. P. (eds.), Meckler, Westport, Conn. (1991).

[8] Krueger, M. W., *Artificial Reality*, Addison-Wesley, Reading, Mass. (1983).

[9] Middlebrooks, J. C., "Narrow-band Sound Localization Related to External Ear Acoustics," *J. Acous. Soc. Am.* **92**, 2607-2624 (1992).

[10] Wenzel, E. M., Wightman, F. L., and Kistler, D. J., "Localization with Non-individualized Virtual Acoustic Display Cues," in *Proc. CHI '91, Human Factors in Computing Systems: Reaching Through Technology*, New Orleans, La., pp. 351-359 (Apr 1991).

[11] Wyshynski, S., and Vincent, V. J., "Full-body Unencumbered Immersion in Virtual Worlds," in *Virtual Reality: Applications and Explorations*, Wexelblat, A. (ed.), Academic Press, New York (1993).

[12] Laurel, B., "Virtual Reality Design: A Personal View," in *Virtual Reality: Theory, Practice, and Promise*, Helsel, S. K., and Roth, J. P. (eds.), Meckler, Westport, Conn. (1991).

[13] Coury, B. G., Boulette, M. D., and Smith, R. A., "Effect of Uncertainty and Diagnosticity on Classification of Multidimensional Data with Integral and Separable Displays of System Status," *Hum. Factors* **31**(5), 551-569 (1989).

[14] Friedhoff, R. M., and Benzon, W., *Visualization: The Second Computer Revolution*, W. H. Freeman, New York (1989).

[15] McCormick, B. H., DeFanti, T. A., and Brown, M. D. (eds.)., "Visualization in Scientific Computing," *Comput. Graphics* **21**(6), special issue (Nov 1987).

[16] Tufte, E. R., *Envisioning Information*, Graphics Press, Cheshire, Conn. (1990).

[17] Robertson, G. G., Card, S. K., and Mackinlay, J. D., "Information Visualization Using 3D Interactive Animation," *Commun. ACM* **36**(4), 57-71 (1993).

[18] Fairchild, K. M., Poltrock, S. E., and Furnas, G. W., "SemNet: Three-dimensional Graphic Representations of Large Knowledge Bases," in *Cognitive Science and Its Applications for Human-Computer Interaction*, Guindon, R. (ed.), Lawrence Erlbaum, Hillsdale, N.J. (1988).

[19] Fuchs, H., Levoy, M., and Pizer, S. M., "Interactive Visualization of 3D Medical Data," *Computer* **22**(8), 46-50 (1989).

[20] Johnson, B., and Shneiderman, B., *Tree-Maps: A Space-Filling Approach to the Visualization of Hierarchical Information Structures*, Tech. Rep. CAR-TR-552/CS-TR-2657, Dept. of Computer Science and Human-Computer Interaction Lab., University of Maryland, College Park, Md. (Apr 1991).

[21] Chandrasekaran, B., Narayanan, N. H., and Iwasaki, Y., "Reasoning with Diagrammatic Representations: A Report on the Spring Symposium," *Artif. Intell. Mag.* **14**(2), 49-56 (1993).

[22] Larkin, J. H., and Simon, H. A., "Why a Diagram Is (Sometimes) Worth Ten Thousand Words," *Cognit. Sci.* **11**, 65-100 (1987).

[23] Pinker, S., "Visual Cognition: An Introduction," in *Visual Cognition*, Pinker, S. (ed.), MIT Press, Cambridge, Mass. (1984).

[24] Cleveland, W. S., and McGill, R., "Graphical Perception and Graphical Methods for Analyzing Scientific Data," *Science* **229**, 828-833 (1985).

[25] Kosslyn, S. M., *Elements of Graph Design*, Freeman, San Francisco (1994).

[26] Kuipers, B., "Modeling Spatial Knowledge," *Cognit. Sci.* **2**, 129-153 (1978).

[27] Sadalla, E. K., Burroughs, W. J., and Staplin, L. J., "Reference Points in Spatial Cognition," *J. Exp. Psychol.: Hum. Learn. Mem.* **6**, 516-528 (1980).

[28] Thorndyke, P. W., and Hayes-Roth, B., "Differences in Spatial Knowledge Acquired from Maps and Navigation," *Cognit. Psychol.* **14**, 560-589 (1982).

[29] Allen, G. L., Siegel, A. W., and Rosinski, R. R., "The Role of Perceptual Context in Structuring Spatial Knowledge," *J. Exp. Psychol.: Hum. Learn. Mem.* **4**, 617-630 (1978).

[30] Hirtle, S. C., and Mascolo, M. F., "Effect of Semantic Clustering on the Memory of Spatial Locations," *J. Exp. Psychol.: Learn., Mem., Cognit.* **12**(2), 182-189 (1986).

[31] Presson, C. C., "Strategies in Spatial Reasoning," *J. Exp. Psychol.: Learn., Mem., Cognit.* **8**, 243-251 (1982).

[32] Baird, J. C., "Studies of the Cognitive Representation of Spatial Relations: I. Overview," *J. Exp. Psychol.: Gen.* **108**, 90-91 (1979).

[33] Trowbridge, C. C., "On Fundamental Methods of Orientation and 'Imaginary Maps,'" *Science* **38**, 888-897 (1913).

[34] Hirtle, S. C., and Jonides, J., "Evidence of Hierarchies in Cognitive Maps," *Mem. Cognit.* **13**(3), 208-217 (1985).

[35] McNamara, T. P., Ratcliff, R., and McKoon, G., "The Mental Representation of Knowledge Acquired from Maps," *J. Exp. Psychol.: Learn., Mem., Cognit.* **10**, 723-732 (1984).

[36] Garling, T., Lindberg, E., Carreiras, M., and Book, A., "Reference Systems in Cognitive Maps," *J. Environ. Psychol.* **6**(1), 1-18 (1986).

[37] Hintzman, D. L., O'Dell, C. S., and Arndt, D. R., "Orientation in Cognitive Maps," *Cognit. Psychol.* **13**, 149-206 (1981).

[38] Kuipers, B. J., and Levitt, T. S., "Navigation and Mapping in Large-scale Space," *Artif. Intell. Mag.* **9**(2), 25-43 (1988).

[39] Hutchins, E., "Understanding Micronesian Navigation," in *Mental Models*, Gentner, D., and Stevens, A. L. (eds.), Lawrence Erlbaum, Hillsdale, N.J. (1983).

[40] Henry, D., and Furness, T., "Spatial Perception in Virtual Environments: Evaluating an Architectural Application," in *IEEE Virtual Reality Ann. Intl. Symp.*, pp. 33-40 (September 1993).

[41] Norman, D. A., *The Psychology of Everyday Things*, Basic Books, New York (1988).

[42] Furness, T. A., III., "Designing in Virtual Space," in *System Design: Behavioral Perspectives on Designers, Tools, and Organizations*, Rouse, W. B., and Boff, K. R. (eds.), North-Holland, New York (1987).

[43] "Virtual Cockpit's Panoramic Displays Afford Advanced Mission Capabilities," *Aviat. Week Space Technol.* **122**(2), 143, 146, 151–152 (Jan 1985).

[44] Fitts, P. M., and Seeger, C. M., "S-R Compatibility: Spatial Characteristics of Stimulus and Response Codes," *J. Exp. Psychol.* **46**, 199–210 (1953).

[45] Williges, R. C., Williges, B. H., and Elkerton, J., "Software Interface Design," in *Handbook of Human Factors*, Salvendy, G. (ed.), Wiley, New York (1987).

[46] Wickens, C. D., "Virtual Reality and Education," in *Proc. 1992 IEEE Intl. Conf. Systems, Man, and Cybernetics*, pp. 842-847 (Oct 1992).

[47] Hamill, B. W., "Intelligent Tutoring Technology: The Emergence of Individualized Instruction," *Naval Res. Rev.* **43**(2), 19–24 (1991).

[48] Hamill, B. W., "Three Issues for Intelligent Tutoring," *Mach.-Med. Learn.* **3**, 169–187 (1989).

[49] Traub, D. C., "Simulated World as Classroom: The Potential for Designed Learning within Virtual Environments," in *Virtual Reality: Theory, Practice, and Promise*, Helsel, S. K., and Roth, J. P. (eds.), Meckler, Westport, Conn. (1991).

[50] Kennedy, R. S., Hettinger, L. J., and Lilienthal, M. G., "Simulator Sickness," in *Motion and Space Sickness*, Crampton, G. (ed.), CRC Press, Boca Raton, Fla. (1987).

ACKNOWLEDGMENTS: Preparation of this article was supported by The Johns Hopkins University Applied Physics Laboratory. The author gratefully acknowledges improvements to the manuscript suggested by John Gersh.

THE AUTHOR

BRUCE W. HAMILL, senior staff psychologist in the Biomedical Research and Engineering Group of the Aeronautics Department, earned an M.A. degree in experimental cognitive psychology and a Ph.D. degree in psycholinguistics at The Johns Hopkins University. His research has focused on visual and cognitive processes involved in interpreting information displays, including visual displays of tactical information and multidimensional displays of acoustic data; tactical decision making; influences of language on problem solving; intelligent tutoring systems science and technology; and cognitive engineering of rule-based supervisory control systems. Dr. Hamill studied visual cognition during his recent tenure of an APL research fellowship in The Johns Hopkins University Psychology Department. His work in visual perception and cognition as they relate to the design of complex computer-based systems has led to an interest in virtual environments to support operational tasks and training.