VIRTUAL REALITY AND EDUCATION

Christopher D. Wickens
Aviation Research Laboratory
University of Illinois at Urbana-Champaign
Savoy, IL 61874

Abstract **Five components of the virtual reality concept are analytically defined: 3D perspective, dynamic rendering, closed loop interaction, inside-out perspective and enhanced sensory feedback. It is argued on the basis of empirical data from a variety of sources, that those components that improve performance by reducing effort may actually inhibit learning or long term retention. Closed loop interaction in contrast, while not reducing effort, appears to have a beneficial effect on retention. The importance for learning of directing users' attention to the link between the VR perspective and a more artificial perspective is also highlighted.**

INTRODUCTION

The goal of the workshop upon which this book is based was to explore the relation between advanced computer technology, signal analysis techniques, and individual differences, in the service of improving computer-based education. Three recent trends in computer technology are particularly relevant to this endeavor. *Adaptive logic* allows computers to present information tailored to the user on the basis of inferred user needs. *Neural networks* represent one important signal analysis technique that may be employed to assess and infer those needs, and advanced dynamic computer graphics represent a potentially powerful means of presenting information to the learner. In particular, adaptive (user sensitive) presentation and dynamic computer graphics have been married in the concept of *virtual reality* (VR) [1, 2, 3]. It is the objective of this chapter to explore the strengths and weaknesses of the VR concept in education, that is the more or less *permanent* transfer of knowledge from the computer to the learner.

The concept of virtual reality is created by an impressive, exciting technology which readily engages the interest of the user. As a consequence, it is reasonable that the concept should be considered by educators as a plausible way of exploiting the technology of advanced computers to improve or expand the learning environment. The present chapter first presents the arguments that may be made for introduction of virtual reality, but then takes a critical look at the constraints on its applicability to education, while drawing on empirical data from simulation, experimental laboratory studies, and basic human factors principles of design. Our approach is to analytically dissect the *components* of VR, to understand those that may benefit learning and those that may not.

This work was supported by the National Science Foundation under Grant No. NSF IRI 90-21270. Dr. John Hestenes was the scientific monitor.

Virtual Reality: Its Components and Justification

Virtual reality is not, in fact, a unified thing, but can be broken down into a set of five features, any one of which can be present or absent to create a greater sense of reality. These features consist of:

1) *Three-dimensional (perspective and/or stereoscopic) viewing vs. two-dimensional planar viewing* [4]. Thus, the geography student who views a 3D representation of the environment has a more realistic view than one who views a 2D contour map.

2) *Dynamic vs. static display.* A video or movie is more real than a series of static images of the same material.

3) *Closed-loop (interactive or learner-centered) vs. open-loop interaction.* A more realistic *closed loop* mode is one in which the learner has control over what aspect of the learning "world" is viewed or visited. That is, the learner is an active navigator as well as an observer. This feature, of course, relates closely to the adaptive characteristics of computer-based learning.

4) *Inside-out (ego-referenced) vs. outside-in (world-referenced) frame-of-reference.* Within the dynamic mode (see 2), the more realistic inside-out frame-of-reference is one in which the image of the world on the display is viewed from the perspective of the learner icon's momentary frame-of-reference. Thus, the explorer of a virtual undersea world will view that world from a perspective akin to that of a camera placed on the explorer's head; rather than, for example, a fixed camera pointing north. For conventional navigational displays, the ego-referenced vs. world-referenced contrast has an analog of fixed north-up vs. rotating track-up electronic maps [5, 6]. It is important to note that the frame of reference can be varied independently for orientation and location.

5) *Enhanced sensory experience.* An integral part of many virtual reality systems is the enhanced feedback which might characterize the tactile feedback from a "data glove" as the hand touches a "virtual object," the proprioceptive feedback from motion through a virtual world, or the auditory feedback emanating from aspects of the environment. We can also include here the use of sound to more realistically characterize the aspects of the environment, although this is not "feedback" in

0-7803-0720-8/92 $3.00 ©1992 IEEE

the formal sense. This is achieved by sophisticated techniques of 3D sound production [7].

These five elements are not entirely independent of one another. For example the difference between frames of reference has little meaning unless the environment is dynamic. However, it is also easy to see how each "layer" of realism can be pealed away or added as desired. In this regard, it is also important to realize that each layer brings with it added costs, or added sources of unreliability in equipment maintenance. As an instructional medium, these costs must be justified in terms of their educational benefit. In this regard, the following justifications may be cited.

1) *Motivational value*. There is little doubt that a major impediment to learning for many students is the absence of intrinsic motivation to master the course material. It may be argued that the intrinsic interest of dynamically interacting with the pictorial learning environment, like a video game, can provide the necessary (but not sufficient) spark of motivation for the student to become initially engaged with the learning environment.

2) *Transfer of the learning environment*. The value of field trips in learning is that they allow the student to directly experience that material which they are to be learning. That is, learning takes place in a real-world context, and its relevance to actual world issues can often be more directly seen. Virtual reality may attempt to capture this "field trip-like" experience.

3) *Different (novel) perspective*. This is an oft-claimed advantage for scientific visualization (a close cousin to virtual reality). The scientist (or other learner) can gain insight from a set of data by exploring it (the interactive component) and viewing it from novel perspectives (the frame-of-reference component) [8, 9].

4) *A "natural" interface*. Much like direct manipulation [10, 11], also a close cousin of virtual reality, the argument for VR is made that the direct and natural navigation through a virtual reality environment, because it captures the essence of walking through a real environment, can be accomplished without the cognitive effort required of many less natural computer interfaces (e.g., those based upon symbolic command strings, or verbal, world-referenced information rather than spatial and ego-referenced information).

Returning to our presentation of the features of VR listed above, we may conceptualize these in terms of two overlapping goals: that of increasing the naturalness of the interface to reduce the cognitive effort required in navigation and interpretation, and that of creating dynamic interaction and novel perspective. In the remainder of this chapter, we argue why it is important to keep the distinction between these goals clear as we consider the conditions in which VR can facilitate or possibly inhibit learning. Specifically, we argue that those features of an interface that may reduce effort and increase performance, may actually reduce retention.

Effort Reduction, Performance, and Learning

Within the human factors community, volumes have been written regarding the concept of mental workload and the desirable design goal of creating systems that do not place unnecessary load upon the human operator's limited cognitive resources [e.g., 12, 13, 14]. Correspondingly, it is also true that many options in flexible advanced computer systems go unused because of the high cognitive effort required to realize their more powerful benefits. In this regard, recent approaches to decision making have modeled the human as an effort-conserving chooser of different decision strategies [15]. As noted above, effort reduction is also a justification for the choice of natural visual-spatial-manual interaction tools, characteristic both of the direct manipulation interface and of virtual reality.

It is easy to support the claim that the tools for the direct manipulation interface are valuable if they eliminate the cognitive workload involved in making transformations from intentions to arbitrary key presses, or from a displayed digital information code to an understanding of its meaning. Unnecessary cognitive workload in the learning environment is well documented to inhibit learning [16]. However, one must be more cautious in assuming that *all* features of virtual reality listed above, that reduce the cognitive effort of interaction and may therefore improve *performance*, will necessarily be of benefit for long term *retention* of the information. This is particularly true to the extent that such features may eliminate effort-demanding cognitive transformations that are necessary to form mental links between different representations of the material to be learned, or if they eliminate effort demanding decisions of where and how to proceed through the virtual space. Several examples may be cited of data suggesting that the five different features of virtual reality, which may support better performance of the operator while interacting with the learning environment, do not necessarily support better long term retention, and in fact, may even inhibit that retention.

We consider the following examples:

(a) Merwin and Wickens [17] compared scientific data visualization performance with 2D planar and 3D (perspective) renderings. Subjects were asked questions that required the integration of information from displays of a complex data set consisting of several companies' status on three economic indicators. Although the integrative questions were answered better when subjects consulted the more integrative 3D graph, a post test in which subjects were asked to describe the economic model that generated the data, revealed no difference between the two formats. Hence, the 3D perspective supported short term performance while the display was present, but had no benefit for longer term retention.

(b) Aretz [6] required pilots to perform a helicopter flight simulation in which they navigated through a virtual world of geometric objects. One group of pilots flew with a track-up (rotating) map, which always presented their navigational information in the same orientation in their forward field-of-view. This "ego-referenced" feature alleviated the cognitive effort required to mentally rotate the map, and is characteristic of the inside-out perspective of virtual reality. This display produced navigational performance that was superior to a group of subjects who flew with a fixed north-up map (world-referenced frame). Yet after the navigation was completed, when both groups were asked to draw a map of the environment through which they had traveled, the latter (fixed map) group showed better retention of the position of the geographical features.

(c) Vicente [18] compared two display designs for supporting diagnosis of complex system failures, a more standard design and an "ecological interface" that presented greater direct visualization of the relation between variables and their relation to underlying thermodynamic principles. While the ecological interface supported better diagnosis of system failures, it did not lead to better retention of specific values.

(d) Yallow [19], in summarizing educational research on "aptitude-treatment interactions," has concluded that providing learners with instructional material in the format (spatial-graphical vs. verbal-words) that is most compatible with their cognitive strengths, will lead to better immediate comprehension of the material, but not to better long term retention.

(e) There has been some evidence from flight simulation research that simulator augmentation via guided training (i.e., guiding the learner through the correct landing path), a technique which is more likely to produce error- free performance, may produce poorer transfer or long term retention of the landing skills, once such augmentation is withdrawn [20]. This finding however has not always been replicated [21], and the issue of how much, or how little errors should be prevented in learning is not well resolved. Interactive programs for teaching computer systems appear to be most effective if some opportunity to make errors is provided, through learner-generated choice, but guided training should modify the learner's progress so that errors are corrected and not repeated nor allowed to cause confusion [22].

The previous five examples suggest that features designed to reduce the workload of processing and/or increase performance will not necessarily improve retention of the processed material. Two further lines of research, addressing reality and closed loop interaction, bear on this dissociation between virtual reality and effort on the one hand, and learning on the other.

(f) Returning to the flight simulator environment, there is by now ample evidence that more realism is not necessarily more conducive to effective learning. For example, the presence of flight simulator motion, an enhanced source of sensory feedback, appears to help performance, but not transfer to the aircraft [23, 24, 25]. Other research by Lintern and his colleagues [especially 26], suggest that added realism will not invariably improve learning. The reasons for these failures of realism probably lie in the diversion of the learner's cognitive resources to those elements of the simulation that are *not* essential to the fundamental understanding of flight dynamics, or in the case of motion, to those sources of information that may be of very little value. Similar conclusions have been drawn regarding the limitations of excessive photographic realism in instruction [27, 28, 29]. Correspondingly, with VR, excessive realism and sensory experience, while "natural," can distract the learner from focusing attention on the key relations to be mastered.

Closed Loop Interaction and Learning

The previous examples have all suggested that various elements present in virtual reality, while facilitating performance, may disrupt retention. However, there is one component of virtual reality, closed loop interaction, for which good evidence exists that it enhances learning. The irony here however is that from the point of view of effort and performance, interactive participation generally produces short term costs, which are then compensated by later gains in knowledge. Several examples of this tradeoff can be cited. Kessel and Wickens [30] found that in understanding tracking dynamics, subjects formed a better mental representation of those dynamics while actively tracking them (closed loop interaction with higher workload) than while passively monitoring an autopilot controlling the same system. The operational flying community has expressed a series of concerns, with a similar interpretation, that higher levels of flight deck automation, designed to reduce workload and so render the pilot's interaction with the aircraft a cognitively simpler one, have left pilots out of touch with the momentary state of the aircraft and have also degraded the accuracy of their mental model of the flight dynamics [31, 32]. In this case the *absence* of active participation and choice (replaced by a more passive viewing experience) has been inferred to cause a degradation in long term retention (i.e., flying skills).

An experimental study by Von Wright [33] supports this argument. Subjects tracked a maze with a series of dichotomous choice points. In the "active" condition, subjects could view ahead of each choice point, which leg was "open" and which was "closed." In the "passive" condition, subjects never made that choice but were forced to travel on the open leg. The results unambiguously indicated better retention of the maze for the active control group.

Work by Foreman, Foreman, Cummings, and Owens [34] indicates that active involvement and choice also enhances the performance of children in a radial-arm-maze type of task. The task was to retrieve a piece of candy from each of eight locations in the maze. During practice sessions, some of the children walked to each location, while others rode in a stroller. Also, whether walking or riding some actively chose their own path, while others were constrained to a path chosen by another child. All of the children then performed the task in testing sessions by walking and choosing their own paths. Those that chose their own paths, whether on foot (walking) or riding in the stroller, were more successful in retrieving the candy. Therefore we can assume that they formed a more accurate cognitive model of the space.

Collectively these diverse results may be summarized by a note of caution: various techniques have been advocated and successfully tested to reduce the cognitive effort of the *user* of computer interfaces; many of these techniques correspond to the five features of virtual reality. While some of these might also improve the long term retention of information that exists within the virtual world, some explicitly do not, and so the techniques of optimal *user* interface design should not be applied wholesale to computer-based *learning* interface design. Furthermore, the one characteristic of virtual reality that seems to be most consistently associated with improved retention--its closed-loop interactive characteristic--is the one that is found to *increase* workload and decrease immediate performance in many systems. This technique presumably, is effective in long term retention because it forces the allocation of task-related resources to address the transformations and connections that are to be mastered, as a component of deeper knowledge.

This final point is worth highlighting because of its relation to the fourth component VR and the proposed benefit of VR relating to an alternative perspective. Much of learning and knowledge involves more than simply the retention of isolated facts. An important facet of knowledge involves understanding the *relation* between facts. Tulving and Thomson's [35] perspective on multiple encoding representation also emphasizes the importance of experiencing the same concept, principle or physical situation from different perspectives (or under different conditions), as a means of enhancing the permanency of knowledge representation. Hence, the educational benefit of the VR experience should be enhanced to the extent that the learner is exposed to material from *both* a VR and a more abstract perspective, and learner attention is directed to the linkages or relatedness between these two perspectives. This might be accomplished either by imposing tasks that force these relationships to be considered for successful task completion, or by visually highlighting the linkages. Both approaches were employed in Aretz's [6] study of spatial navigation in a helicopter discussed above. In both cases the emphasis on linkage between the more realistic (forward view) and abstract (north-up map) renderings were successful in fostering better long term retention of the environment.

Visual Momentum

In previous pages we have outlined the case for the learner to receive alternative viewpoints, perspectives, or format representations of the same underlying data scheme. A concern with virtual reality, for example, is that it only presents the most "egocentric" representation of the material to be mastered, and this needs to be coupled with a more abstract, world-centered perspective of the same material. At the same time, the urge for diversity of representations, may be at odds with the desirable feature of maintaining consistency. Fortunately, these two competing goals--diversity and consistency--can be partially reconciled through the principle of visual momentum.

The concept of visual momentum represents an engineering design solution proposed to address the issues of becoming cognitively lost as the display user traverses through multiple displays pertaining to different aspects of the same system or data base [36]. The concept was originally borrowed from film editors, as a technique to provide the movie viewer with an understanding of how successively viewed film cuts relate to each other [37]. When applied to the viewing of successive display frames, either of actual space (e.g., maps), or "conceptual space" (e.g., topologically related components in a process control plant, nodes in a menu or data base, or graphical representations of data), the concept of visual momentum may be captured in terms of four basic guidelines.

a) *Use consistent representations*. This guideline of course reiterates a principle that was set forth above. Unless there is an explicit rationale for changing some aspects of a display representation, aspects should not be changed. However, when it is necessary to show new data, or present a new representation of previously viewed data, the principles of visual momentum dictate that display features should show the relation of the new data to the old. The next three guidelines show how this may be accomplished.

b) *Use graceful transitions*. When changes in representation will be made over time, abrupt discontinuities may be disorienting. For example, on an electronic map the transition from a small scale wide angle map to a large scale close-up will be cognitively less disorienting if this change is made by a rapid but continuous "blowup."

c) *Highlight anchors*. An anchor may be described as a constant invariant feature of the displayed "world," whose identity and location is always prominently highlighted on successive displays. For example, in aircraft attitude displays that might be viewed successively in various orientations, the direction of the vertical (or the horizon) should always be prominently highlighted. In map displays, which may be reconfigured from inside-out to outside-in, in order to accommodate different task demands, a salient and consistent color code might be used to highlight both the northerly direction and the heading direction [38]. In Aretz's [6] study of helicopter navigation, discussed above, he successfully used an anchor by portraying the angle subtended by the forward field of view as a "wedge" on north-up map. In displays used to examine components of a complex chemical or electrical process, the direction of causal flow (input-output) could be prominently highlighted. In the design of "you are here" maps, visually prominent landmarks in the forward view, highlighted on the map, offers such an anchor [39].

A corollary principle of the preceding is that when successive display frames are introduced, each new frame should include overlapping areas or features with the previous frame, and these common landmarks should be prominently highlighted (here again, color is an effective highlight).

d) *Display continuous world maps*. Here we refer to a continuously viewable "map" of the world, always presented from a fixed and compatible perspective. Within this map the "current identity" of the active display is always highlighted. This is a feature of the topographic maps produced by the U.S. Geological Survey in which a small map of the state is always viewable in the upper left hand corner, with the currently displayed quadrant highlighted in black. Knepp, Barrett, and Sheridan [40] developed a display concept to support information search through, and retrieval from, a multidimensional data base: the display featured a small, but consistently oriented picture of the full data base in the form of a cube, and the currently examined item was highlighted. A study by Vicente and Williges [41], nicely supported the concept of "world maps" in information retrieval from a hierarchically-organized data base in which users had experienced problems of "cognitive disorientation." Vicente and Williges found that the presence of a map of the file-organization, and of a cursor highlighting the momentary position within the file structure provided significant benefits to user "orientation."

In sum, the various facets of visual momentum, by highlighting how different viewed perspectives correspond with each other, should facilitate creation of "linkages" between these perspectives, thereby assisting learning. As a safeguard, these linkages should limit the frustrating experiences of "lostness" or "disorientation" that may occur when confronting an inside-out orientation.

CONCLUSION

In conclusion, we have argued that the goals of good interface design for the user and good design for the learner, while overlapping in many respects, are not identical. A key feature in this overlap is the concern for the reduction in effort; many of the features of virtual reality may accomplish this reduction. Some of these features, like the naturalness of an interface which can replace arbitrary symbolic command and display strings, clearly serve the goals of both. But when effort-reduction features of virtual reality serve to circumvent cognitive transformations that are necessary to understanding and learning the relationships between different facets of data, or of a body of knowledge, then a disservice may be done. This caution should be kept in mind as virtual reality concepts are introduced into education. Also care should be taken to ensure redundancy of presentation formats, exploit the utility of visual momentum, exploit the benefits of closed-loop interaction, and use other principles of human factors design.

REFERENCES

[1] M.A. Clarkson, "An easier interface," *BYTE*, pp. 277-282, February 1991.

[2] H. Rheingold, *Virtual reality*. New York: Summit Books, 1991.

[3] J. Furness, "Testimony before Senate subcommittee on science, technology, and space," *Committee on Commerce, Science, and Transportation*, May 8, 1991.

[4] C.D. Wickens, S. Todd, and K. Seidler, *Three-dimensional displays: Perception, implementation, and applications* (Technical Report ARL-89-11/CSERIAC-89-1). Savoy, IL: University of Illinois Aviation Research Laboratory, 1989 (also CSERIAC SOAR 89-001, AAMRL, Wright-Patterson AFB, OH, December).

[5] K. Harwood and C.D. Wickens, "Frames of reference for helicopter electronic maps: The relevance of spatial cognition and componential analysis," *The International Journal of Aviation Psychology*, vol. 1, pp. 5-23, 1991.

[6] A.J. Aretz, "The design of electronic map displays," *Human Factors*, vol. 33, no. 1, pp. 85-101, 1991.

[7] D.R. Begault and E.M. Wenzel, "Techniques and applications for binaural sound manipulation in human-machine interfaces," *The International Journal of Aviation Psychology*, vol. 2, no. 1, pp. 1-22, 1992.

[8] G. Zorpette, The main event. *IEEE Spectrum*, vol. 26, no. 1, 28, 1989.

[9] J.S. Cohen, "Visualization explores the depths of visual perception," *National Center for Supercomputing Applications Newsletter, Access*, vol. 3, no. 6. University of Illinois at Urbana-Champaign, 1989, pp. 11-12.

[10] E.L. Hutchins, J.D. Hollan, and D.A. Norman, "Direct manipulation interfaces," *Human-Computer Interaction*, vol. 1, no. 4, pp. 311-338, 1985.

[11] R.J.K. Jacob, "Direct manipulation in the intelligent interface," in *Intelligent interfaces: Theory, research and design*, P.A. Hancock and M.H. Chignell, Eds. North Holland, Netherlands: Elsevier Science Publishers B.V., 1989, pp. 165-212.

[12] S.G. Hart and C.D. Wickens, "Workload assessment and prediction," in *MANPRINT: An emerging technology. Advanced concepts for integrating people, machines and organizations*, H.R. Booher, Ed. New York: Van Nostrand Reinhold, 1990, pp. 257-300.

[13] P.A. Hancock and N. Meshkati, *Human mental workload*. Amsterdam, The Netherlands: North Holland Press, 1988.

[14] C.D. Wickens, "Processing resources and attention," in *Multiple task performance*, D. Damos, Ed. London: Taylor and Francis, 1991.

[15] J.R. Bettman, E.J. Johnson, and J.W. Payne, "Consumer decision making," in *Handbook of consumer behavior*, T.S. Robertson and H.S. Kassarjin, Eds. Prentice Hall, 1991, pp. 50-84.

[16] O. Sweller, P. Chandler, P. Tierney, and M. Cooper, "Cognitive load as a factor in the structuring of technical material," *Journal of Experimental Psychology: General*, vol. 119, pp. 176-192, 1990.

[17] D.H. Merwin and C.D. Wickens, "2D vs. 3D display for multidimensional data visualization: The relationship between task integrality and display proximity," *Proceedings of the 35th Annual Meeting of the Human Factors Society*. Santa Monica, CA: Human Factors Society, 1991.

[18] K.J. Vicente, *Supporting knowledge based behavior through ecological interface design*. Unpublished doctoral dissertation. University of Illinois at Urbana-Champaign, Department of Mechanical and Industrial Engineering, Urbana, IL, 1990.

[19] E. Yallow, *Individual differences in learning from verbal and figural materials* (Aptitudes Research Project T.R. No. 13). Stanford, CA: Stanford University, School of Education, 1980.

[20] G. Lintern and S.N. Roscoe, "Visual cue augmentation in contact flight simulation," in *Aviation psychology*, S.N. Roscoe, Ed. Ames: Iowa State University Press, 1980.

[21] J.M. Koonce and G. Lintern, "Visual augmentation and scene detail effects in flight training," *Proceedings of the Sixth International Symposium on Aviation Psychology*. Columbus, OH: Department of Aviation, Ohio State University, 1991.

[22] Carroll and Carrithers, "Blocking learner error states in a training-wheels system," *Human Factors*, vol. 26, no. 4, pp. 377-389, 1984.

[23] C.O. Hopkins, "How much should you pay for that box?" *Human Factors*, vol. 17, no. 6, pp. 533-541, 1975.

[24] J.M. Koonce, "Predictive validity of flight simulators as a function of simulator motion," *Human Factors*, vol. 21, pp. 215-223, 1979.

[25] G. Lintern, "Flight simulation motion systems revisited," *Human Factors Society Bulletin*, vol. 30, no. 12, pp. 1-3, 1987.

[26] G. Lintern, S.N. Roscoe, and J. Sivier, "Display principles, control dynamics, and environmental factors in pilot training and transfer," *Human Factors*, vol. 32, pp. 299-317, 1990.

[27] K. Spencer, *The psychology of educational technology and instructional media*. London: Routledge, 1988.

[28] F.M. Dwyer, "Adapting visual illustrations for effective learning," *Harvard Educational Review*, vol. 37, pp. 250-263, 1967.

[29] J.K. Schmidt and K.P. Kysor, "Designing airline passenger safety cards," *Proceedings of the 31st Annual Meeting of the Human Factors Society*. Santa Monica, CA: Human Factors Society, 1987, pp. 51-55.

[30] C.J. Kessel and C.D. Wickens, "The transfer of failure-detection skills between monitoring and controlling dynamic systems," *Human Factors*, vol. 24, pp. 49-60, 1982.

[31] E.L. Wiener and R.E. Curry, "Flight deck automation: Promises and problems," *Ergonomics*, vol. 23, pp. 995-1012, 1980.

[32] D. Hughes, "Glass cockpit study reveals human factors problems, *Aviation Week and Space Technology*, pp. 32-35, August 7, 1989.

[33] J.M. Von Wright, A note on the role of "guidance" in learning. *British Journal of Psychology*, vol. 48, pp. 133-137, 1957.

[34] N. Foreman, D. Foreman, A. Cummings, and S. Owens, "Locomotion, active choice, and spatial memory in children," *The Journal of General Psychology*, vol. 117, pp. 215-232, 1990.

[35] E. Tulving and D.M. Thomson, "Encoding specificity and retrieval processes in episodic memory," *Psychological Review*, vol. 80, pp. 352-373, 1973.

[36] D.D. Woods, "Visual momentum: A concept to improve the cognitive coupling of person and computer," *International Journal of Man-Machine Studies*, vol. 21, pp. 229-244, 1984.

[37] J. Hochberg and V. Brooks, "Film cutting and visual momentum," in *Eye movements and the higher psychological functions*, J.W. Senders, D.F. Fisher, and R.A. Monty, Eds. Hillsdale, NJ: Erlbaum, 1978.

[38] A.D. Andre, C.D. Wickens, L. Moorman, and M. Boschelli, "Display formatting techniques for improving situation awareness in the aircraft cockpit," *The International Journal of Aviation Psychology*, vol. 1, no. 3, pp. 205-218, 1990.

[39] M. Levine, "You-are-here maps: Psychological considerations," *Environment and Behavior*, vol. 14, pp. 221-237, 1982.

[40] L. Knepp, D. Barrett, and T.B. Sheridan, "Searching for an object in four or higher dimensional space," *Proceedings of the 1982 IEEE International Conference on Cybernetics and Society*. Seattle, WA, 1982, pp. 636-640.

[41] K.J. Vicente and R.C. Williges, "Accommodating individual differences in searching a hierarchical file system," *International Journal of Man-Machine Studies*, vol. 29, pp. 647-668, 1988.