Rudolph P. Darken
Department of Computer Science
Naval Postgraduate School
Monterey, CA 93940
darken@cs.nps.navy.mil

Terry Allard
Cognitive and Neural Science
and Technology Division
Office of Naval Research
Arlington VA 22217-5660

Lisa B. Achille*
Naval Research Laboratory
Washington, DC 22202

Spatial Orientation and Wayfinding in Large-Scale Virtual Spaces:

An Introduction

1 Introduction

> "I have coasted this lake, in search of skins, afore the war, and have been here already; not at this very spot, for we landed yonder, where you may see the oak that stands above the cluster of hemlocks."
>
> "How, Pathfinder, can you remember all these trifles so accurately?"
>
> "These are our streets and houses—our churches and palaces. Remember them, indeed! . . ."
>
> *The Pathfinder*, James Fenimore Cooper (1840)

Just as the Pathfinder used the lake and the oak tree to reconstruct his environment, so do we structure our environment with streets and houses, landmarks and guiding principles to aid spatial orientation and wayfinding. The basic process of navigation—extracting information, forming mental representations, and using that representation for route planning and moving about—transcends the physical elements of the environment itself. In practice, we use whatever the environment gives us to solve navigation problems as they arise, in the process, continually refining and updating our internal model of the external environment. Although the virtual environments we speak of may be vastly different in their appearance from the Pathfinder's world, the principles underlying spatial orientation and wayfinding in large-scale virtual spaces have many commonalities.

This special issue of *Presence* is devoted to the principles and mechanisms underlying the design and usability of large-scale, immersive virtual environments. What cognitive, perceptual and motor skills are required for orientation, training transfer, and wayfinding? What is the nature of the internal representation of virtual spaces that allow accurate predictions of movements through and interactions with the virtual world? What are the relative merits of different interaction techniques on the acquisition of complex spatial layouts? Ultimately, how can virtual worlds be designed that minimize disorientation and maximize spatial understanding within the virtual world and corresponding real-world counterparts for training transfer (including long-term retention) or teleoperation?

Current simulation technology is limited by the expense and limited availability of dedicated simulators. The advent of compact, portable, reconfigurable and affordable virtual environment simulators will have enormous impact in the private sector in both research and development as well as in the entertainment industry (National Research Council, Committee on Modeling and Simulation, 1997). The independent control of sensory and motor displays should permit a careful dissection of cause and effect in perceptual and motor

Presence, *Vol. 7, No. 2, April 1998, 101–107*

---

*Now at: Crewstation Technology Laboratory, Naval Air Warfare Center, Aircraft Division, Patuxent River, MD 20670-1906 studies of human behavior similar to the great breakthroughs in speech perception in the 1950s that were enabled by independent control of distinctive features in speech synthesis. We can expect a similar explosion of knowledge as virtual environments become better, cheaper, and more widely available.

Immersive virtual environment simulation is currently being explored as a training solution for a variety of military applications, including shipboard firefighting, urban warfare tactics, and shiphandling. For example, virtual environment training was demonstrated to reduce the number of errors and time to traverse the ship by experienced Navy firefighters with no previous exposure to virtual environment technologies (Williams et al., 1997). These studies continue to raise several basic questions of general interest: Do people tend to remember nonstandard spaces such as the rounded walls and acute angles found shipboard as if they were standard spaces of the more familiar right-angle world as might be indicated by studies of map-reading (Chase, 1983)? Do individual differences such as previous experience with ships improve the acquisition of their unusual dimensions and configuration? Is a visual training environment the optimal way to encode the spatial layout of a complex space that will be navigated under the degraded visual conditions induced by smoke and poor lighting? What is the value added of direct exploration of the real world versus ‘‘fly-through’’ metaphors typical of virtual environments? These questions address fundamental issues in the perception of self, motion, distance, and scale that are components to spatial knowledge in everyday life as well as in virtual environments.

This special issue begins with a focus on basic research into spatial orientation (Lackner and DiZio) and mental representations (Colle and Reid). The next three papers address the use of virtual environments as training aids for spatial knowledge. The first concerns general spatial knowledge acquisition through a virtual environment (Waller, Hunt, and Knapp). The second is a study of distance estimation (Witmer and Kline), and the third is a study of locomotion effects on path integration with emphasis on direction estimation (Chance, Gaunet, Beall, and Loomis). Finally, the issue concludes with two papers on performance aids to navigation. Loomis, Golledge, and Klatzky present a study on an acoustic guidance cue that is intended for a navigation system for the blind, but could easily be adapted for use in any virtual environment target-acquisition task. Ruddle, Payne, and Jones discuss the effects of familiarization and simple orientation aids on navigation performance.

2 Mental Representations

The questions of what information we extract from our environment and how that information is subsequently structured in and recalled from human memory for later use are at the heart of this special issue. Given the seemingly infinite flexibility we have in constructing virtual environments and the fundamental role of navigation in those environments, a better understanding of these issues is in order.

The major theme that runs throughout each of the articles in this issue is that of mental representations of space (also known as *cognitive maps;* Howard and Kerst, 1981). Whether we’re talking about improved performance in navigating a virtual environment (Ruddle et al.) or using a virtual environment as a training aid for navigating a real environment (Waller et al.), a well-developed mental representation is essential to the success of the task. The awareness of individuals of their changing knowledge state as they navigate in virtual environments and learn new environments will impact our ability to measure their performance and the efficacy of various training approaches, navigational cues, and suggested strategies. There is much to be learned about knowledge self-monitoring techniques practiced by individuals while they acquire and adjust their internal representation of the virtual space.

Is configuration (or survey) knowledge metric or topological? This question is addressed by Colle and Reid as well as by Witmer and Kline. A metric representation would imply that we directly encode distances and directions between locations in our environment. Alternatively, if the knowledge is topological, then only the relative spatial relationships would be encoded.

The Landmark-Route-Survey (LRS) model of spatial knowledge first described by Siegel and White (1975), while the most widely accepted theory of spatial representation to date, cannot directly account for the seemingly instantaneous development of configuration knowledge in certain situations as opposed to other cases in which it does not seem to develop at all, even after extremely long periods of exposure. If spatial knowledge is topological, then the notion of "metric distance" is probably irrelevant. There are instances of a scaling phenomenon in which spatial knowledge acquired from secondary sources (e.g., maps) is actually quite well-developed but initial performance in the primary environment is low due to an error in scaling the mental representation to the real world. This error is quickly overcome by looking for redundant cues in the environment and resolving what is seen with what is expected. We have noticed this phenomenon in highly experienced sport orienteers in a recent study (Darken and Banker, in press). Participants reported that initial confusion caused by the scaling error is followed by a "snapping" phenomenon where the world that is seen is instantaneously snapped into congruence with the mental representation. This is further supported by a significant decrease in navigation errors after this occurrence.

The "room effect" described by Colle and Reid would seem to account for some of the differences in the development of configurational knowledge, but there is some question as to its extensibility to highly unstructured spaces such as natural environments. It may be that in these cases, natural environments must be visually subdivided to facilitate the room effect. There would not seem to be a need to channel the environment into rooms and halls since it has been shown both by Colle and Reid and also by Darken and Sibert (1996) that vision does not have to be occluded nor movement restricted for regional barriers to exist.

Lackner and DiZio take this idea further, suggesting that a mental representation of space is not only linked to the way that spatial knowledge was acquired but also to the way it is subsequently accessed. Their "wrong room" phenomenon suggests that people acquire specific local configurations in a global context. Orientation in a local context is disrupted when the local and global spatial layouts are made inconsistent by rotating a familiar local environment with respect to the global environment in which it is normally embedded. Similarly, virtual environments can be thought of as local environments embedded within a global space. It may be necessary to align the local and global coordinates in order to provide a consistent spatial representation of the virtual space. A similar phenomenon can be found in studies of mental rotation of spatial representations where configuration knowledge gained from a "North-up" map must be rotated when that environment is entered from a direction other than the South (Franklin and Tversky, 1990; Presson, DeLange, & Hazelrigg, 1989; Sholl, 1987). It is critical that spatial coordinate systems are locally and globaly congruent.

Lackner's comments on Mark Twain's *Life on the Mississippi* are reminiscent of current training procedures for U.S. Navy and Marine helicopter pilots at Camp Pendleton, California. While on navigation training flights, pilots often follow the same egress and ingress routes. Even though pilots have seen the exact same terrain only a few minutes earlier from the opposite direction, they are usually unaware of the actual identity of the checkpoint. Useful features in this environment tend to look extremely different from alternative angles and altitudes of approach. There seems to be no substantial benefit to seeing a checkpoint from one perspective if it is to be approached later from a different perspective.

The matching feedback model described by Passini (1984) captures these phenomenon fairly well. A particular image (stimulus) is expected from some vantage point. If what is seen does not match what was expected, the response demands a resolution to this conflict. In this case, the sensation is that of being "almost" right but wrong enough to trigger a reparation response. This work in total suggests that if we build virtual environment trainers for environment familiarization, such as studied by Waller et al., Koh (1997), Darken and Banker (in press), and Williams et al. (1997), it may be important to vary the entrance and exit points to some degree.

Waller's separation of the problem area into components of *interface fidelity* and *environment fidelity* is a good idea. While both Witmer and Kline and Chance et al. focused on interface fidelity, Waller makes a point of separating it from the representation of the environment itself. However, it should be noted that these two subcategories are strongly interwoven. We cannot assume that more fidelity implies better performance. A recent study by Koh (1997) suggests that the real world is by no means always the best way to acquire spatial knowledge of a space. There may be better representations as well as better interfaces. The best virtual environment terrain-familiarization trainer would be one that results in the highest performance on navigation tasks in the real world with the shortest amount of training time *regardless* of what the virtual environment looks like or how the interface works.

3 Virtual Locomotion

Navigation must be seen as a process. We often make the mistake of only seeing it as its end result—locomotion—navigation's most visible attribute. However, the cognitive subtasks that drive locomotion such that we know where to go and how to get there are an integral part of the overall task. Certainly, locomotion has an effect on mental representation as discussed by Chance et al. and Witmer and Kline.

It has often been suggested that the best locomotion mechanism for virtual worlds would be natural locomotion (e.g., walking, running, crawling, and so on). This suggestion is based on a number of questionable assumptions concerning distance and direction estimation and maneuverability.

Proprioceptive information serves to calibrate the motions of the body to movements in space. Loomis et al (1992) showed that inclusion of proprioceptive feedback allows for more accurate distance and direction estimation in blind walking tasks. If this is true, it may account, in part, for the performance differences in Waller's study. Without proprioceptive feedback during training, the virtual environment groups may have been unable to compensate for the loss of the visual channel when participants are blindfolded in the testing phase.

Given the highly sensitive nature of the proprioceptive feedback mechanism, performance on Witmer's traversed distance estimation task may have been lower than expected because of sensory conflicts between expected and actual responses from the device. The very nature of walking on treadmills of this sort is suspect due to significant differences between approximated walking on a treadmill and actual walking (Darken, Cockayne, and Carmein, 1997).

It is interesting to find that whereas Witmer and Kline report that natural locomotion does not help in estimating distance, Chance et al. suggest that it does help in estimating bearing. Witmer and Kline show that distance estimation does not seem to be significantly better when a treadmill is used than when an abstract technique is used such as a joystick. However, they used a unidirectional treadmill in a very constrained task. It is possible that a closer approximation to natural walking would have faired better. A closer approximation would allow for better maneuverability and flexibility in the task but possibly at the expense of usability. The Omni-Directional Treadmill is one such device (Darken et al., 1997). Although this device was never tested on a distance estimation task, the increased maneuverability it allowed introduced serious balance problems making maneuvering tasks very difficult.

A long-standing argument for wide field-of-view displays is for the purposes of maneuverability. It has often been suggested that the reason users of narrow field-of-view displays "hang-up" in doorways and corners is because they have no peripheral vision (Witmer and Kline). This issue has recently been addressed by Robertson, Czerwinski, and van Dantzich (1997) where they found that wider field-of-view displays alone do not improve maneuverability on these sorts of tasks. This is not to say that wide field-of-view displays are not preferable to their narrow counterparts, but only that this attribute alone is not the problem.

4 Methodology

There are a number of methodological issues addressed in this collection of articles that may be somewhat foreign to our community. It would seem that in some fashion we would like to know what the performance curves (proficiency on navigation tasks or training transfer with respect to exposure time) look like for a variety of interfaces and environments. As more studies like these are completed and published, we can begin to see the shape of these curves relative to one another. These performance curves could be used to estimate the necessary exposure time to meet a specific performance level or possibly to determine the best medium (e.g., map, virtual environment, or both) given some constraint on exposure duration. The methodological quandary here is that it is extremely difficult to measure navigation performance at more than one point in time. Once a subject is exposed to an environment and measured, it is difficult to conceive of an experimental design that would allow that subject to be measured at a future point in time because the act of measurement is exposure in itself and consequently will distort future measurements (a psychological Heisenberg principle).

The blindfolded testing phase in Waller et al. is an attempt to overcome this problem by measuring within subject performance levels on the maze walking task over all six repetitions. Had the task been visually dominant, learning would have clearly been taking place during each of the six trials each participant completed. The blindfold aspect of the task was meant to allow for the measurement of performance over time, but questions remain as to whether or not blindfolding the participants fundamentally changed the task.

There is another issue here involving the duration of the training phase of experiments like Waller's. In one case, the duration of exposure to training materials and/or environments could be kept constant with the dependent measure being how well the participant does on the navigation task given some constant training period. However, in practice, all people are different and, consequently, the amount of time needed to train is probably different. Methodologically speaking, we account for this by having large numbers of subjects. But sampling large populations is often not possible. Alternative methods include training to asymptotic performance or assessing differential stability, both of which can be quite error prone (Damos, 1991; Bittner, 1979). Both methods would imply allowing for a variable exposure period wherein the participant must perform some task in the training environment at some level of proficiency before going on to the testing phase. One of the problems with this method is that the proficiency task in one treatment (e.g., a virtual environment condition) may be different from that of another treatment (e.g., a map-reading condition). How do we resolve this issue?

The well-documented individual differences in spatial ability both between individuals and genders is cause for further study (McGee, 1979). Waller et al. used the Guilford Zimmerman Spatial Orientation test as a measure of natural ability and also observed a strong gender difference in their experiment. While spatial ability is multidimensional, many of the tests used to measure its subcomponents correlate well with each other, and with general intelligence (Lohman, 1979). There are other tests relevant to the study of navigation having to do with spatial visualization, perceptual speed, and spatial scanning that are also relevant to this area of research (Ekstrom et al., 1976). Results of these tests can be compared both within the experiment to other participants as well as to national averages that are publicly available.

At a minimum, careful attention must be paid during data analysis to the variance that may be due to individual differences in abilities. There is evidence that individual differences in verbal and mathematical skills can impact performance on spatial tasks such as navigation, particularly when there are opportunities to use verbal strategies to compensate for unpracticed spatial skills (Chipman and Wilson, 1985). A better understanding of the range of individual differences in skills and their effects on spatial problem-solving and navigation strategies may inspire ways to control for this factor in the design of experimental tasks and allow the development of more effective (remedial) training approaches for individuals with lower spatial skills. There is evidence that spatial skills are not completely innate (i.e., they may be under the influence of experience and training) and can increase with appropriate training (Carpenter and Just, 1986; Connor, Serbin and Schackman, 1977).

There is a long-standing debate over how to measure configuration (or survey) knowledge. This problem probably starts with some difference of opinion as to exactly what constitutes configurational knowledge as opposed to route knowledge. However, most agree that configuration knowledge is a well-connected network of locations (or landmarks) with multiple potential paths between them. The most obvious method to measure configurational knowledge is map drawing but this approach has been strongly criticized because of differences in drawing ability. Most recent methods have centered on distance and direction estimation only; however, this estimation does not take into account path generation from point to point. A person may be able to reasonably estimate the direction and distance to a remote location without being able to plan a path to get to it. In this issue, there are examples of both map-drawing or free-recall methods (Colle and Reid) and pointing tasks (Colle and Reid; Chance et al.; Ruddle et al.). If we believe configurational knowledge to be a necessary prerequisite to superior navigation performance, we will want to define it and agree on benchmark or common metrics to measure it.

5 Conclusions

Today, we would undoubtedly refer to the Pathfinder as an "expert" navigator. How did he become so skilled in navigating his environment? What navigational principles were abstracted from his natural environment? The typical city dweller would not fare so well on navigation tasks when placed in a natural environment such as the Pathfinder's. Was the Pathfinder just especially adept at spatial orientation or was this ability acquired over time and how? If the Pathfinder were to be brought into a typical urban environment, might he have some of the same difficulties that most of us would have in his environment?

Much work remains to be done. A wide range of virtual environment issues are of critical importance to our broad and diverse multidisciplinary community of psychologists, cognitive scientists, computer scientists, and design engineers. Answers to these critical questions are essential to the eventual application of virtual environment technologies. These issues include individual differences in spatial ability; spatial skill development; training time; user/task analyses; performance metrics; and the design of interfaces, interactions and virtual world simulations. Further studies are needed on scaled or otherwise distorted sensorimotor environments, spatial orientation and control in teleoperation applications, and the design of abstract and/or nonterrestrial information spaces. The wealth of current research in this area has prompted *Presence* to announce a *second* special issue on Spatial Orientation and Wayfinding in Large-Scale Virtual Spaces. Potential contributors are directed to the call for papers in this issue.

References

Bittner, A., Jr. (1979). Statistical tests for differential stability. *Proceedings of the Human Factors Society 23rd Annual Meeting,* 541–545.

Carpenter, P. A., & Just, M. A. (1986). Spatial ability: An information processing approach to psychometrics. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence.* (Vol. 3). Hillsdale, NJ: Lawrence Erlbaum Associates.

Chase, W. G. (1983). Spatial representations of taxi drivers. In D. R. Rogers & J. A. Sloboda (Eds.), *Acquisition of symbolic skills.* New York: Plenum.

Chipman, S. F., & Wilson, D. M. (1985). Understanding mathematics course enrollment and mathematics achievement: A synthesis of the research. In S. F. Chipman, L. R. Brush, & D. M. Wilson (Eds.), *Women and Mathematics: Balancing the equation* (pp. 275–328). Hillsdale, NJ: Lawrence Erlbaum Associates.

Connor, J. M., Serbin, L. A., & Schackman, M. (1977). Sex differences in response to training on a visual spatial test. *Developmental Psychology,* 13, 293–296.

Damos, D. (1991). Dual-task methodology: Some common problems. In D. L. Damos (Ed.), *Multiple-task performance* (pp. 101–119). Washington, DC: Taylor & Francis.

Darken, R. P., & Banker, W. P. (In press). Navigating in natural environments: A virtual environment training transfer study. *Proceedings of VRAIS '98.*

Darken, R. P., Cockayne, W. R., & Carmein, D. (1997). The omni-directional treadmill: A locomotion device for virtual worlds. *Proceedings of ACM UIST '97* (pp. 213–221). Banff, Canada.

Darken, R. P., & Sibert, J. L. (1996). Wayfinding strategies and behaviors in large virtual worlds. *Proceedings of ACM SIGCHI 96,* 142–149.

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Manual for kit of factor-referenced cognitive tests.* Princeton, N.J.: Educational Testing Service.

Franklin, N., & Tversky, B. (1990). Searching imagined environments. *Journal of Experimental Psychology: General, 119* (1), 63–76.

Howard, J. H., & Kerst, S. M. (1981). Memory and perception of cartographic information for familiar and unfamiliar environments. *Human Factors, 23*(4), 495–504.

Koh, G. (1997). *Training spatial knowledge acquisition using virtual environments,* Masters Thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology.

Lohman, D. F. (1979). *Spatial ability: A review and reanalysis of the correlational literature.* Technical Report No. 8, School of Education, Stanford University.

Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance 18*(4), 906–921.

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin, 86*(5), 889–918.

National Research Council, Committee on Modeling and Simulation (1997). *Modeling and simulation: Linking entertainment and defense.* Washington, DC: National Academy Press.

Passini, R. (1984). *Wayfinding in architecture.* New York: Van Nostrand Reinhold.

Presson, C. C., DeLange, N., & Hazelrigg, M. D. (1989). Orientation specificity in spatial memory: What makes a path different from a map of the path? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*(5), 887–897.

Robertson, G., Czerwinski, M., & van Dantzich, M. (1997). Immersion in desktop virtual reality. *Proceedings of ACM UIST '97* (pp. 11–19). Banff, Canada.

Seigel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. In H. W. Reese (Ed.), *Advances in child development and behavior* (pp. 9–55). New York: Academic Press.

Sholl, M. J. (1987). Cognitive maps as orienting schemata. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13*(4), 615–628.

Williams, F. W., Tatem, P. A., Farley, CDR J. P., Tate, D. L., Sibert, L., King, LCDR T., Hewitt, D. H., Siegman, C. W. III, Wong, J. T., & Toomey, LT T. A. (1997). *Virtual environment firefighting/Ship familiarization feasibility tests.* NRL Technical Report 97-9861. Washington, DC: Naval Research Laboratory.