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Nathaniel I. Durlach, et al.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

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TRAINING SPATIAL KNOWLEDGE ACQUISITION USING VIRTUAL ENVIRONMENTS

(1 February 1997 TO 31 January 1998)

Nathaniel I. Durlach, et al.,

Massachusetts Institute of Technology
Research Laboratory of Electronics
77 Massachusetts Avenue, Room 36-767
Cambridge, Massachusetts 02139
617-253-2534
durlach@cbgrle.mit.edu

Prepared for:
Dr. T. Allard
Cognitive & Neural Sciences
Office of Naval Research (Code 342)
800 N. Quincy Street
Arlington, VA 22217-5660
703-696-4502 voice
703-696-8343 fax

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1. EXECUTIVE SUMMARY

This report summarizes the work done by MIT in Year 2 (1 February 1997 through 31 January 1998) of the ONR Grant N00014-1-96-0379 entitled "Training Spatial Knowledge Acquisition Using Virtual Environments." It has been written by Dr. Thomas E. v. Wiegand, Nathaniel Durlach (PI), Glenn Koh, S. Brian Fitch, and Rebecca Lee Garnett.

During this second year of the program, we have continued along the line of development charted during Year 1. We have completed the preliminary experiment on the acquisition of spatial knowledge by means of brief training in a number of VE-based simulations, and begun analysis of the comparative effectiveness of immersive, non-immersive, and 3D model-based virtual environments in training configurational knowledge of a small architectural space. We have completed initial development and testing of a small, cost-effective prototype locomotion interface device, the "finger walker," to enable more natural locomotion in virtual environments than is possible through use of a joystick. In addition, we have continued work on the development of a room-scanning robot, a device for collecting texture-map data from large complex venues. Finally, our experience of the difficulty entailed in developing photorealistic models of a complex large-scale environment has also led us to begin work on the development of a new VE construction system allowing us to import two-dimensional building floorplan files and to automatically attach textures to walls, doors, windows, and other objects within the virtual building.

The body of this report, which is devoted to describing the above-mentioned work, is supplemented by two theses (Appendices 1 and 2) related to this work.

2. PROGRESS REPORT

Our work during Y2 can be summarized under the following headings: (1) Experiment on spatial knowledge acquisition in an architectural space; (2) Development of a VE-based navigational interface; and (3) Development of a room scanner.

During Y1 of this grant, we initiated development of facilities (mainly software) and selection of experimental venues and procedures to study VE-assisted training of spatial behavior. Although we initially planned to conduct experiments in Y2 in a complex architectural space (a four-story, 89,000 sq. ft. warehouse containing lots of discarded furniture and equipment), we soon realized when attempting to model this space that our facilities were totally inadequate for such an effort. This realization led us to (1) emphasize more heavily experimental work in simpler venues (see Sec. 2.1 below) and (2) devote serious attention to the development of improved methods for constructing VE models of architectural spaces (see Sec. 2.3 below).

2.1 Experiment

A preliminary experiment was designed at the end of Year 1 for the purpose of testing our proposed processes for VE modeling as well as our experimental procedure. The goal of this experiment was to establish the efficacy of virtual environment technology as a training medium for spatial knowledge acquisition, and to determine the extent to which configurational knowledge of a space can be acquired through the process of exploring a high-resolution photo-realistic VE simulation of an actual space. Completion of this preliminary experiment, and the analysis of data gathered from its participants constituted the principal work accomplished in this area during Year 2.

2.1.1 Method. As described in our Year 1 report, the venue selected for this preliminary experiment consisted of a portion of the seventh floor of MIT building 36, a site which had previously been used for the low-end feasibility study described in Sec. 2.3.3 of the Year 1 report. A VE model of this venue was developed using the same hardware/software facilities as those intended for use in creating the VE model of the large-scale warehouse. The test task employed was intended to evaluate subjects' configurational knowledge of the space after a brief period of training in one of four conditions: RW (Real World); VE (Immersive VE); NVE (Non-Immersive VE); and Mod (Model). Following training in one of these conditions, the subjects were brought to the actual venue, positioned at each of four given reference points within the real space (stations), and asked to estimate the location of a number of landmarks within the real space by reporting the azimuth of each landmark and its range relative to the location of the station.

For all training conditions, subjects were informed in advance about the task they would be asked to perform at the completion of the training period. Training included 10 minutes of free exploration under the conditions of the specific training method. For those in the RW condition, a 10 minute self-guided exploration of the actual space was the only training provided. In the other cases (VE, NVE and Mod), subjects were given a brief opportunity to familiarize themselves with the training technology to be used prior to the beginning of the 10 minute training period, during which the VE representation of the actual space was provided. Subjects were not informed of the specific landmarks they would be asked to identify during the subsequent testing phase of the experiment, but were told to note the relative spatial configuration of the venue, rather than to try to memorize the characteristics of individual objects in the space.

In the VE condition, subjects used a headmounted display (HMD) to view the representation of the space, and a joystick for a first-person simulated walkthrough within it. The NVE condition used the same equipment and procedures, except that the representation was viewed on a 21" monitor rather than through an HMD. In the Mod condition, subjects viewed on the monitor a miniature exocentric 3D model of the space, essentially a 3D equivalent to a map of the space, that could be manipulated using a mouse. This model allowed for a change in the subjects' point of view as well as the opportunity for viewing "inside" the space (as though the ceiling of the space had been removed).

2.1.2 Equipment. The VE walkthroughs used in this study were run on modified Easyscene software from Coryphaeus running on an SGI Onyx RE/2. The Onyx was equipped with two R4400 processors operating at 150 Mhz and 128 MB of RAM. The Easyscene software was modified to allow for a first-person walkthrough through a developed model with collision detection and joystick support added. Modifications were also made to enable support for the headmounted display and adaptation of multiple viewpoints and control methods for immersive, non-immersive, and exocentric experimental conditions.

The headmounted display used was a Virtual Research VR4. The device has a horizontal resolution of 350 lines, a vertical resolution of 230 lines, and a 60 degree field of view. It was not stereo-enabled for this study. Orientation of the HMD was determined by an attached Polhemus 3Space Fastrak sensor which provided orientation and position information to the walkthrough software for translation to a properly corresponding image in the HMD. Positional translation was accomplished through the use of a joystick.

Estimation of azimuth during the testing phase of the experiment was accomplished using a pointer attached to a tripod-mounted protractor. Subjects were transported from station to station in a wheelchair, with their eyes blindfolded to prevent the possibility of learning contamination from visual cues other than those available at the testing stations. Landmarks selected as pointing targets were obscured from the subjects' view by the interposition of walls and doors.

The architectural model of the space was constructed, using Coryphaeus Designers' Workbench software, from blueprints of MIT Building 36. Objects within the space were fully texture mapped from within Designer's Workbench, with textures obtained by photography with both a Nikon N6006 camera with film scanned at 1280x1024 by Konica, and a Kodak DC20 Digital Science digital camera. Texture maps were edited using Kodak PhotoEasy software and Adobe Photoshop, and imported into Designers' Workbench for application to the building model.

2.1.3 Subjects. For this experiment, 36 subjects were recruited from the student population of

MIT. None had prior experience of the experimental venue. All were compensated for their time, and all signed the COUHES agreement on the use of human subjects. Each was randomly assigned to one of the four training conditions. Following the experiment, each was asked to fill out two surveys, one on the virtual environment and one on the experience of immersion. Subjects whose bearing estimates were more than 90 degrees offset from the actual target were considered to be disoriented and their results were excluded from the analysis. Each subject's angular and range estimation was tested at the first experimental station by asking him/her to point at an object that could be seen; these estimates were later used for calibration purposes. No correct-answer feedback was given at any time during the testing phase.

2.1.4 Results. The most accurate estimates of the bearing to objects seemed to come from the groups trained in the non-immersive Virtual Environment (NVE) and Model conditions, with averaged mean errors of 10.07 (1.76) and 10.11 (1.94) degrees respectively. The groups trained in the Real World (RW) and (Virtual Environment) conditions had error scores of 11.92 (1.58) and 12.18 (1.69) respectively.

In the estimation of distance to objects, again the Model and NVE groups seemed to fare best, with averaged mean errors of 19.46 (4.5) feet and 19/36 (4.97) feet, followed by the VE and RW conditions at 24.76 (4.1) feet and 33.61 (4.06) feet respectively.

Bearing and distance estimates from each subject were combined with the position of the initial pointing station to derive the cartesian coordinates of the subjects' estimated location of the landmark objects. As before, the Model and NVE conditions fared best, with average mean errors of 25.49 (5.15) feet and 27.48 (5.69) feet, followed by VE and RW conditions at 33.14 (4.77) feet and 40.29 (4.64) feet respectively.

The magnitude of the error vector can be used as an indicator of the ability of the subject to point to a specified object. Error values from each pair of station and target were found for each subject, then averaged of all subjects in their respective experimental conditions. By combining bearing and distance tasks, the results should give an indication of the subjects' knowledge of the configuration of the space. In this analysis, those who trained in the RW condition performed most poorly, while the NVE and Model conditions performed similarly well. Subjects in the RW and VE conditions performed especially poorly when the specified objects were located at a long distance from the station.

An ANOVA for bearing error (obtained F of 1.22; criterion F of 2.37) indicates that there is not enough evidence to conclude that any of the training conditions had an effect on the performance of the bearing estimation test. This does not indicate that there are no differences in the training methods with regards to this test, but that the variance between the different training conditions is not sufficiently larger than the variance within training conditions.

An ANOVA for mean distance error (obtained F 7.02; criterion F of 2.37) indicates that there is some correlation between the training conditions and performance in the distance estimation task. With regard to this task, the RW training condition gave particularly poor results, with the NVE and Model conditions faring well.

The cartesian localization analysis of the bearing and distance estimation tasks is the metric which perhaps comes closest to the idealized measure of spatial knowledge: it indicates how well the subjects learned the spatial locations of the targeted landmarks. ANOVA results in an Obtained F of 5.25 and Criterion F of 2.37, again indicative of a positive correlation between training method and test performance.

2.1.5 Discussion. That the best results in terms of accuracy of bearing and distance estimation came from the group trained with the virtual model of the space is not surprising, given the fact that map training can be highly effective, and the Model provides the advantages of a 3D map plus photorealistic rendering of the venue. In this respect it is analogous to the WIM, or World-in-Miniature (Stoakley, Conway, Pausch 1995), which may perhaps provide better training results than training in a fully immersive virtual environment. Subjects trained in the Model condition had access to the same realistic rendering of the virtual venue as did those trained in the other simulation groups (VE and NVE), but were not limited to the egocentric walkthrough method of learning the space; rather, they could acquire their knowledge of the space from alternative and manipulable points of view.

The relatively poor performance of those trained in the Real World condition can be explained in a number of ways. First, it is possible that the level of detail in the real world, being greater than that which could be rendered in any of the virtual representations, proved to be distracting during the period when the subjects were attempting to learn the configuration of the space. Second, it is possible that those who trained in a computer-generated condition had the advantage of a greater degree of interest in the task than those who simply had 10 minutes to walk around and look at the actual space.

The advantage of the NVE condition over the VE condition can perhaps be explained by the better resolution, refresh rate, and color provided by the monitor as compared to the HMD, as well as by the subjects' relative unfamiliarity with the HMD equipment compared with their previous experience using a monitor and joystick combination.

The primary purpose of this study was to determine whether adequate knowledge of an architectural venue can be obtained through training in a virtual simulation rather than in the real world venue. Results show that this is indeed the case, since the groups trained in the computer simulations of the space performed as well or better than those trained in the real world on the measures chosen for comparison. However, the comparisons among the various forms of VE training were less conclusive. The exocentric model training condition performed well, as did the non-immersive VE condition. ANOVAs showed a high variance in the RW and VE conditions and a relatively lower variance and degree of error in the NVE and Model conditions, even though the same model was used in both conditions. This suggests that there may be independent advantageous factors in the NVE and Model training conditions which, if combined, could lead to the development of a highly effective computer-based virtual environment training method.

While the intersubject variance proved to be large, it was shown in this study that a virtual environment training system can be as effective as a real-world experience with respect to the localization of landmarks. With a baseline established and with the development of a runtime virtual walkthrough system, it may be possible to focus in the future on developing and testing training techniques and establishing their efficacy in the training of spatial knowledge acquisition.

For additional details on this experiment and its results, see Appendix 1 (Koh, 1997).

2.2 Locomotion Interface Development

One important aspect of a VE training program designed to facilitate the acquisition of knowledge about a space involves providing the user with a plausible means of moving about within the virtual environment. As planned during Year 1, our research program in Year 2 has focused on the development and testing of an inexpensive interface that allows a user to "finger walk," or simulate, by means of finger motion, the activity of walking within and through a virtual environment. While there seems to be some direct relationship between the development of spatial knowledge and the amount and type of effort expended in moving from place to place (as one expends effort while walking in the real world), the choice of a motion-control interface for exploration within virtual environments may be constrained by factors such as cost. The interface which we have designed as part of our Year 2 work is one which operates within the well-known "walking metaphor" of motion control, making use of a low-friction pad that allows the user to "walk in place" by means of moving his fingers, and an electric field sensing system that monitors the position of the fingers on the pad. The interface effectively tracks the user's movement along the surface of the pad for input into the virtual environment.

The potential benefits of this work are twofold. First, it is possible that many of the expected advantages of a full-scale walking interface can be realized in a more cost-effective manner by means of a scaled-down, finger-walking interface. Secondly, the experience gained in developing such a finger-walking interface using a slippery pad may be useful for subsequent work on a slippery-floor walking interface.

The finger walking device, as developed and described in Appendix 2, is an inexpensive, compact, easy-to use interface for providing locomotion within virtual environments. The operator uses a natural walking-like motion with fore and middle fingers, with minimal equipment attached to his body. The input to the user interface is a tracking of the change in the electric field created by the user's fingers. The output to the virtual environment from the finger walker is a velocity vector, consisting of a magnitude and a direction.

The operation of the interface is easy and straightforward. First, the user sits down at the computer, workstation or other setup for viewing the virtual environment. The user then attaches transmitter electrodes to his fingers for tracking. Next, the user places an HMD on his head, or position himself before a standard computer monitor, to view the virtual environment. Finally, the user places his fingers on the finger walker pad and begins moving his fingers in a walking-like motion. The finger walker and the virtual environment software perform the calculations which update the position of the user in the virtual environment. The user interface consists of five distinct stages of operation: signal detection, data acquisition, translation, special operation instructions, and velocity computation. Hardware systems detect the electric field and send the data to a computer for processing. The finger walker software package then manipulates the electric potential received from an analog to digital card to compute a velocity vector.

During operation, the coordinates of the user's fingers and the velocity of the user through the virtual environment is displayed within an on-screen window, which also provides a graphical position map and a directional compass. A separate window tracks the movement of the user through the virtual environment by drawing a line along the path of the user as determined by the magnitude and direction variables.

Initial tests of the interface have provided evidence to support the electric field proximity sensor as an efficient method by which to track the movement of the user. The finger walker appears to be fairly accurate when tracking the position of the fingers across the pad, and the tracking window shows that the device provides an effective means of moving through a virtual environment. Some limitations of the present device include a lack of memory of past system events, and extreme sensitivity of the hardware to slight changes in the position of the finger, as well as to noise in the system. It is expected that improvements to the system can be introduced to eliminate these difficulties, and that the effectiveness of the "walking" motion and expenditure of effort on the user's ability to estimate distances accurately in the virtual environment should then be subject to future experimental study.

For further details on this work, see Appendix 2 (Fitch, 1998).

2.3 Room Scanner

2.3.1 Progress on room scanning robot and work on scanning rack

During Y2, we have continued the development of the room scanner, a novel device for capturing environmental texture from the viewpoint of the VE participant. This is achieved using an eye-level camera with wide angle (110 degree) lens moved in precise increments in parallel to the observed detail, with distances and orthogonality being preserved through the use of alignment lasers. A software controller steps the camera along a section of wall, capturing image frames at regular intervals. A tiling tool then takes these frames and pastes them together to form long strips of texture for each wall section. These sections are then attached to specific polygons within the floorplan, or set as the default texture for a particular room or class of objects. Once textures have been associated with a floorplan, the resulting data is exported as a list of 3D polygons and associated textures. These post-processing tools are further described in a later section.

In the early part of this project year, we made steady progress on aspects relating to image data collection, sensors, and software; however, a number of problems arose relating to mechanical issues which have led us to (temporarily) modify the form of the scanning device.

One of the major successes has been that of integrating the QuickCam image capture hardware with the QuickTime multimedia storage and compression format. Within the standardized API environment provided by Apple and the adherents to the QuickTime standard (such as Connectix, the producers of QuickCam), we have been able to put together our image capture software in a way that preserves the refinement of the Macintosh Interface, and also maintains compatibility with future upgraded versions of any of the component pieces. In addition to being able to use the graphical image compression and storage aspects of the QuickTime format, we have included acoustic impulse response information keyed to location and coordinate information from floorplans. These files are directly browsable using QuickTime players available on many platforms, and serve as a stream of "raw data" for our VE-generating post-processing tools.

We have encountered a number of mechanical difficulties with the mobile robot-based room scanner on which we began working last year. These difficulties arise primarily from irregularities in real-world floor surfaces. Even in the relatively clean environment of our laboratory, the navigation issues arising in controlling motion over irregular floor surfaces are not trivial. We initially expected that open-loop control of motion along a straight line would yield acceptable performance for initial tests, but we quickly discovered that even small drifts in the motion would result in unacceptable distortions of the incoming texture data. We had hoped to be able to delay work on the laser guidance part of the system until after some of the more basic issues were finished, but this became impossible. Therefore, in a parallel effort, we began working out the guidance routines using a separate small robot purchased for the purpose. The result of this effort was a set of routines for tracking a laser using either a linear photodiode array, or a more general routine for tracking the laser using a reflected image of the laser as detected by the CCD camera acquiring the texture images.

Ultimately, we would like to utilize this work to guide a room-scanning robot, but in our experiments we have seen that the tracking routine introduces its own motion anomalies, which, when combined with some of the secondary mechanical considerations of the mobile robot (maintenance of precise verticality, vibration, etc.) lead us to put the approach on hold in favor of a simplified but very practical form of the room scanner (involving a scanning rack).

As an outcome of software development for managing the texture acquisition process, we found it useful to describe the texture records not as arbitrarily-long ribbons but rather as standard blocks of nominally 5 foot length. This description arose from consideration of both filing organization issues as well as issues involving the ultimate application of the textures to polygons within a real-time VE application. In considering the requirements, namely, that of very precise orthonormal image scanning throughout the block length, we decided to put together a scanning rack to provide a controlled path for the camera to travel along. This approach, although in some ways superficially similar to taking photographs of each block with a normal camera, still preserves the "viewpoint-free" perspective that allows the edges of each block to be seamlessly stitched (as described in the Y1 report) without viewpoint irregularities.

The layout of the rack-based system is fairly simple. A carriage containing the stepper motor and camera is mounted on a toothed rack which is suspended between a pair of supports. The rack is positioned parallel to the surface (wall) to be scanned using one of a number of possible positioning aids (string, stick, crossed laser beams). After the camera traverses the span of the rack, the assembly is slid over to the next position, in a motion that is easy to repeat consistently. In this way the blocks of texture are captured one by one for each room and corridor of the venue.

2.3.2 Introduction to TOADS (Three-dimensional Open-ended Architectural Database System.

Much thought and effort in Y2 has been spent addressing the major bottleneck in the creation of complex VE simulations: the construction of 3D models and the acquisition of photo-realistic textures for those models. Moreover, the prospect of having to sort out gigabytes of texture data and assign these files to the appropriate polygons of a model made us realize that some automated system for organizing and linking this information would be necessary if we were to realize any benefit from the large amount of additional data collected with the scanner.

The automated VE Generation system simplifies both of these tasks by allowing users to import two-dimensional DXF floorplan files (commonly available for many installations, including all of the buildings at MIT) and then automatically attach textures to walls, doors, windows, and other objects within the building. The tool can take DXF files, which normally consist of an uncoordinated collection of lines and polygons, group them logically into rooms, and classify each object as one of several possible object types (e.g. door or wall.) In conjunction with the scanner, the graphical interface allows straightforward and unambiguous association of particular scans with particular places in the plan view.

3. OVERVIEW OF YEAR 3 WORK PLAN

Our main effort during Y3 will be directed towards completion of the VE-construction system. Additional work will include further analysis of the data obtained in the experiment described in Sec. 2.1 above, preparation of this material for publication, initiation of a "white paper" on VE-assisted spatial training for use by ONR in their program planning, and preparation of a renewal proposal to obtain funds for continuing this work. Two major foci of our planned future work are (1) the development of a VE training system that includes Virtual Worlds in Miniature (WIMs) to serve as 3D maps and (2) the development of VE-assisted methods for assessing basic spatial skills and abilities and for enhancing these skills and abilities.

4. APPENDICES

Appendix 1: Glenn Koh: Training Spatial Knowledge Acquisition Using Virtual Environments. Master's Thesis, MIT Department of Electrical Engineering and Computer Science, 1997.

Appendix 2: Sanford Brian Fitch: "The Finger Walker: A Method to Navigate Virtual Environments. Master's Thesis, MIT Department of Electrical Engineering and Computer Science, 1998.

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