Preliminary findings on a virtual environment targeting human mental rotation/spatial abilities

A Rizzo[1], J G Buckwalter[1], P Larson[2], A van Rooyen[2], K Kratz[2], U Neumann[3], C Kesselman[4] and M Thiebaux[4]

[1]Alzheimer's Disease Research Center, University of Southern California, 3715 McClintock Ave., Los Angeles, CA 90089-0191

[2]Fuller Graduate School of Psychology, 180 North Oakland Ave., Pasadena, CA. 91101

[3]Computer Science Dept., University of Southern California, Los Angeles, CA 90089

[4]Information Sciences Institute, University of Southern California, 4676 Admiralty Way, Suite 1001, Marina del Ray, CA 90292

[1]*arizzo@mizar.usc.edu*

ABSTRACT

Virtual Reality technology offers the potential to create sophisticated new tools which could be applied in the areas of neuropsychological assessment and cognitive rehabilitation. If empirical studies demonstrate effectiveness, virtual environments (VE's) could be of considerable benefit to persons with cognitive and functional impairments due to acquired brain injury, neurological disorders, and learning disabilities. Testing and training scenarios that would be difficult, if not impossible, to deliver using conventional neuropsychological methods are being developed which take advantage of the attributes of virtual environments. VE technology allows for the precise presentation and control of dynamic 3D stimulus environments, in which all behavioral responding can be recorded. A cognitive domain where the specific advantages found in a virtual environment are particularly well-suited, is with human visuospatial ability. Our paper outlines the application of a virtual environment for the study, assessment, and possible rehabilitation of a visuospatial ability referred to as mental rotation. The rationale for the Virtual Reality Spatial Rotation (VRSR) system is discussed, and the experimental design that is being used to collect data from a normal, aged 18 to 40 population is presented. Our research questions are then outlined and we discuss some preliminary observations on the data that has been collected thus far with the system.

1. INTRODUCTION

Virtual reality technology is increasingly being recognized as a potential tool for the assessment and rehabilitation of human cognitive and functional processes (Foreman et al, 1997; Pugnetti et al, 1995; Rizzo and Buckwalter, 1997; Rose, 1996). Virtual environments (VE) allow for the creation of dynamic stimulus environments, in which all behavioral responding can be recorded. This technology could potentially offer testing and training options that are unavailable with the use of conventional neuropsychological methods. It is our belief that computer-generated interactive simulated environments can be used to assess and rehabilitate cognitive abilities, much like an aircraft simulator tests and trains piloting abilities. Flight simulators have been used for over fifty years to train both military and commercial pilots, and the benefits of this technology have been demonstrated (Johnston, 1995). In this regard medical applications that use VE's are now showing promise as a way to train the visualization and procedural skills needed to perform surgery (Satava, 1996). Persons with cognitive and functional impairments due to traumatic brain injury, neurological disorders, and learning disabilities, could also benefit from the advantages of VE-based assessment and rehabilitation. VE's are now being developed and tested which focus on component cognitive processes including: memory (Rose et al, 1997), executive functions (Pugnetti et al, 1998, Mendozzi et al, 1998), spatial skills (Foreman et al, 1997; McComas et al, 1998; Rizzo et al, 1998a), and attentional processes (Brown et al 1997; Wann et al, 1997). VE functional training scenarios have also been designed to test and teach basic activities of daily living such as: street-crossing (Strickland, 1997; Inman et al, 1997), common object recognition (Strickland, 1997), supermarket shopping (Cromby et al, 1996), use of public transportation (Mowafy and Pollack, 1995), and wheelchair navigation (Inman,1997). VE projects such as these give hope that the 21st century will be ushered in with new and exciting tools to advance a field that has long been mired in the methods of the past.

Our work has focused on the development of a VE for the study, assessment, and rehabilitation of a visuospatial ability referred to as Mental Rotation (MR). Everyday life situations which rely on this ability to use imagery to turn over or manipulate objects mentally are quite common. These include automobile driving judgments, organizing items in limited storage space, sports activities, and many other situations where one needs to visualize the movement and ultimate location of physical objects in 3-D space. High level mathematics performance has also been linked, in large part, to MR ability (Casey et al, 1995). Indeed, in a recent Los Angeles Times interview, it was noted that world renown physicist, Stephen Hawking, "…translates mathematics into geometry, and turns around geometrical shapes in his head." (Cole, 1998). The initial MR investigations began almost 30 years ago with the work of Shepard and Metzler (1971) who tachistoscopically presented pairs of two-dimensional perspective drawings to subjects and required them to make judgments as to whether the 3-D objects they portrayed, were the same or different (see figure 1). A near perfect linear relationship was found between the amount of angle rotation difference between the pairs of objects, and the reaction time to decide whether or not the objects were the same or different. Since precise mathematical relationships between hypothesized mental representations and behavioral performance are relatively rare, MR has been the focus of much research over the years.

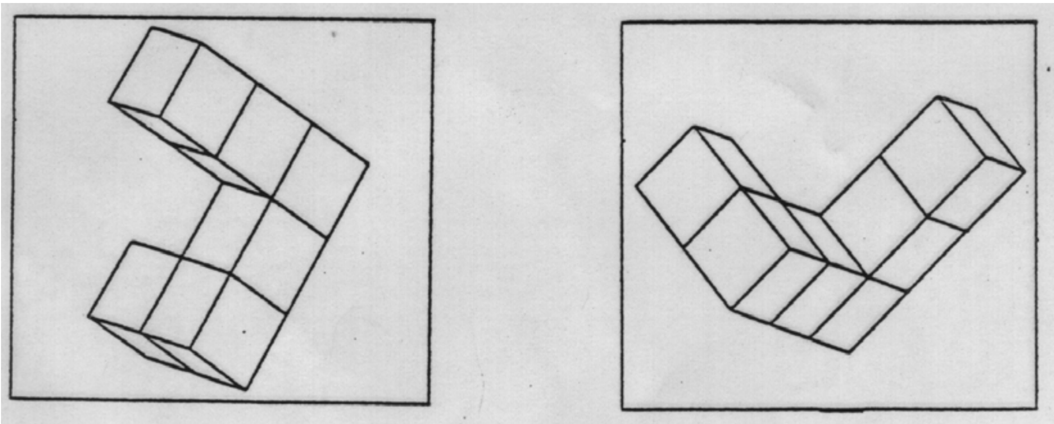

Figure 1. *Mental Rotation Stimuli*

Tests of spatial ability, including the MR variable, have commonly been used for the study of brain/behavior relationships particularly regarding sex differences in cognition. Mental rotation ability has been shown to produce the most consistent and sizable sex differences, in favor of males, in the cognitive literature (Voyer et al, 1995). Consequently, a lively literature has emerged examining MR, in addition to cognitive variables where female advantages have been shown (i.e., verbal fluency and fine motor skills, etc.). Studies have revealed differential cognitive performance due to such hormonal factors as onset of menopause, estrogen and testosterone administration, and stage of the menstrual cycle (Gouchie and Kimura, 1991; Kampen and Sherwin, 1994; Silverman and Phillips, 1993) However, these findings remain controversial. Several studies have attempted to explain cognitive sex differences as the product of sociocultural influences, and on non-specific testing performance factors related to the use of timed tests and "reluctance to guess" factors (Richardson,1994; Qubeck, 1997; Delgado and Prieto, 1996). Also, while it has also been suggested that the effect size in gender differences is decreasing with time, meta-analytic research argues against such conclusions (Masters and Sanders, 1993; Voyer et al, 1995).

Spatial ability is an important domain to consider in the assessment of neurological disorders, traumatic brain injury, and neuropathological conditions of aging. Spatial orientation abilities have been shown to be an important variable in the differential diagnosis of dementia. For example, research indicates that victims of Alzheimer's disease have an 84% incidence of spatial orientation impairments compared to only a 4% incidence in frontotemporal dementia (Miller et al, 1997). Impairments in spatial orientation were also shown to be more common in Alzheimer's disease compared to both normal elderly and those with vascular dementia (Gianotti et al, 1992; Signorino et al. 1996). Similar impairments have been observed following the occurrence of traumatic brain injury and stroke (Lezak, 1995). In light of these issues, (which are on-going research interests at our lab at the USC Alzheimer's Disease Research Center), and our interest in the potential usefulness of virtual technologies, we began development of the Virtual Reality Mental Rotation/Spatial Skills Project.

Traditional measures used for the assessment of mental rotation have produced intriguing findings, yet lack the precision needed to better understand this spatial ability. The most common test uses two-dimensional stimuli that portray three-dimensional objects and requires complete mental processing of the stimuli without any motoric involvement (Vandenberg and Kuse, 1978; Peters et al, 1995). We have developed and are collecting data on a measure of spatial rotation ability that is administered in a VE to more precisely evaluate and possibly rehabilitate this cognitive process. The use of a VE for the assessment of cognitive abilities allows for better standardization of stimulus presentation as well as quantification of multiple characteristics of the stimuli.Further, responses of the subjects can be quantified on a range of characteristics that cannot be evaluated using traditional psychometric instruments. The combination of greater control and description of the stimuli along with more precise measurement of responses should allow for characterization of the cognitive processes involved in spatial skills in a more discrete fashion than is possible with standard measures. Comparison of performance in the VE with performance on standard measures offers the potential to better understand this crucial cognitive ability. Also, by examining changes in spatial performance following VE exposure, useful rehabilitation options may emerge and be developed. This is based on our view that immersive VE-delivered physical rotation training with the MR stimuli could help improve imaginal mental rotation abilities. This assertion is bolstered by a recent study which concluded that rotary object manipulation and mental object rotation share a mutual process that is believed to direct the dynamics of both imagined and actual physical object reorientation (Wohlschlager and Wohlschlager 1998). By conducting future studies on this VE system with the elderly, and persons with brain injury or neurological disorders, the feasibility and effectiveness of this novel technology for assessment and rehabilitation purposes with these groups can be addressed.

The useful application of VE's in the areas of assessment and rehabilitation of cognitive/functional abilities, while intuitively appealing, cannot progress until basic cost/benefit, feasibility, and clinical effectiveness issues are examined. These include factors relating to the selection of appropriate training and target variables, system costs, clinical population characteristics, optimal levels of presence/immersion, interface and navigational demands, side effects, learning and generalization, and data analytic strategies. These issues are more fully explored in other papers, along with detailed descriptions and rationales for VE's addressing psychological and cognitive variables (Rizzo et al, 1998a,b). Our research program has been designed so that many of these issues can be economically addressed, while at the same time, data can be collected regarding our cognitive variable of interest -- visuospatial mental rotation. This approach allows for the investigation of VE specific concerns (side effects, generalization), factored with both clinical applications (assessment and rehabilitation of clinical groups) and general experimental studies (sex difference investigations). This multi-purpose approach was a definate "selling point" in getting acceptance and resources for the development of this system.

The following describes our Virtual Reality Spatial Rotation (VRSR) system and details the experimental design that is being used to collect data from a normal, aged 18 to 40 population. We will outline our research questions and present some preliminary observations on the subjects that have been evaluated with the system. Also, at the time of the conference, it is expected that we will have results available from the full data set.

2. METHOD

2.1 Subjects

Fifty-four subjects (23 males and 31 females) between the ages of 18-40 were tested. Subjects included employees recruited at the Information Sciences Institute of the University of Southern California, graduate students from the Fuller Graduate School of Psychology, and undergraduate students from the University of Southern California and California State University at Los Angeles.

2.2 Virtual Reality System

The Virtual Reality Spatial Rotation (VRSR) system uses an ImmersaDesk drafting table format virtual prototyping device. The Pyramid Systems ImmersaDesk employs stereo glasses and magnetic head and hand tracking. This projection-based system offers a type of VR that is semi-immersive. It features a 4 X 5-foot rear-projected screen positioned at a 45 degree angle. The size and position of the screen give a wide-angle view and the ability to look down as well as forward.

The VRSR assessment and training system was designed to present a target stimulus that consists of a specific configuration of 3D blocks within a virtual environment (similar to Figure 1). The stimuli appear as "hologram-like" three dimensional objects floating above the projection screen. After presentation of a target stimuli, the participant is presented with the same set of blocks (control object) that needs to be rotated to the orientation of the target and then superimposed within it. The participant manipulates the control object by grasping and moving a sphere shaped “cyberprop” which contains a tracking device and provides tactile feedback. Upon successful superimposition of the control and target objects a “correct” feedback tone is presented and the next trial begins.

2.3 Procedures

The experimental sessions take place over a two hour period. After informed consent is obtained, basic demographic information, computer experience and usage, and spatial activities history (Newcombe et al, 1983) are recorded. Female subjects complete a brief survey of reproductive history. Next, a baseline measure of mental rotation ability is assessed using a redrawn version (Peters et al, 1995) of the Mental Rotation Test (MRT-A) of Vandenberg & Kuse (1978), a twenty item, 2-dimensional paper and pencil task. Subjects then complete a comprehensive neuropsychological battery administered under standard conditions. Following the completion of the neuropsychological battery, subjects complete the Motion History Questionnaire (Kennedy and McCauley, 1984) and Simulator Sickness Questionnaire (Kennedy et al, 1993), which includes a pre-VE exposure symptom checklist. Experimental subjects then participate in the fifteen minute VE task that both assesses and trains mental rotation abilities. After 5 non-rotational practice trials, each subject’s VE spatial rotation baseline performance is assessed over 20 trials using a VE version of the items from the pencil and paper MRT. Next, 100 training trials of increasing stimulus complexity are administered. After a one minute break, the original 20 VE MRT trials are administered again to measure changes in VE spatial rotation ability. Control subjects are given a filler task (crossword puzzle) of matching duration instead of the VE exposure. The Simulator Sickness Questionnaire, which contains a post-VE exposure symptom checklist is then given to each subject. Finally, an alternate form of the paper and pencil MRT is administered to assess changes in mental rotation performance.

2.4 Testing Instruments

The neuropsychological battery included a diverse collection of instruments. Mental rotation ability is assessed using the Mental Rotation Test. This test uses line drawings of block stimuli and consists of two 10-item sections in which the subject is required to match two of the four choices to a target figure. Incorrect choices are mirror images of the target or alternative block configurations. Standard administration provides for a five minute time limit. The alternate form of the MRT uses the same drawings but reorders their presentation and switches position of the target stimuli.Verbal attention and mental control is assessed with the Digit Span Forward and Backward test from the Wechsler Adult Intelligence Scale-Revised (Wechsler, 1981). Visuoconstruction abilities are measured by the Block Design subtest of the WAIS-R. The Trail-Making Tests A and B are used to evaluate executive control processes and attention (Army Individual Test Battery, 1944). The Judgment of Line Orientation test is used to evaluate visuoperceptual skills (Benton et al, 1978). The California Verbal Learning Test is employed to assess verbal learning and memory (Delis et al, 1983). Nonverbal memory is evaluated by the Visual Reproduction subtest of the Wechsler Memory Scale-Revised (Wechsler, 1987). These tests are all commonly used for neuropsychological assessment of these cognitive processes and as such have widely used normative information available. Finally, surveys of simulator sickness and motion sickness history are administered.

2.5 Data Analysis and Research Questions

We have collected data from a variety of domains. These included: 1. Neuropsychological performance on tests of cognitive functioning (attention, verbal and visual memory, visuospatial abilities, etc.); 2. Demographic factors (education, gender, reproductive history, etc.); 3. Spatial Activity History (a self-report scale of participation in everyday activities that contain spatial components); 4. Computer Usage History Questionnaire (a self-report measure that we have developed which assesses computer use, programming activities, use of computer games, etc.); 5. Side effects assessment; and, 6. VE data: all movement is digitized in real time, allowing for playback of each response. While we anticipate developing more sophisticated analytic techniques, we are currently analyzing time to completion per trial, ratio of actual movement path to optimal movement path as a measure of efficiency, and various compiled measures, such as the total time for first 20 VRSR items vs. last 20.

From this data, we will attempt to answer the following research questions:

1. What is the level of side-effects that occur with use of the VRSR system and are there sex differences?
2. Is the occurrence of side effects low enough to justify a future VRSR trial with elderly subjects, persons with dementia, persons with traumatic brain injury, and individuals with other neurological impairments?
3. What is the relationship between various performance measures on the VRSR system and performance on standard neuropsychological tests of attention, memory, and other visuospatial variables?
4. How well does the paper and pencil MRT predict performance on the VRSR system and how does this vary contingent on how VRSR performance is quantified (i.e., total time vs. efficiency ratio)?
5. Do the same sex differences that are seen on the pencil and paper MRT appear on VRSR performance?
6. In women, do these performances vary contingent upon hormonal differences due to day of the menstrual cycle?
7. Will advanced data collection methods of the VRSR system enable us to delineate common gender specific strategies for spatial rotation?
8. Does VRSR performance improve with practice (100 training trials) as seen by comparing 20 pre-training VR MRT items with 20 identical post-training VR MRT items (intra-method generalization)?
9. Does VRSR training improve post-training pencil and paper MRT performance in participants who score low on the pretest MRT compared to practice effects in the control group. (inter-method generalization)?
10. If training and transfer effects are found (questions 8 and 9), are there sex differences?
11. Does history of self-reported computer usage play a role in the above?
12. Does history of self-reported spatial activities influence the above?

3. RESULTS AND CONCLUSIONS

While we are still collecting the data, a few anecdotal observations can be made. There were minimal negative side effects reported by participants in the VRSR condition. Of those reported, they have been mainly related to fatigue. Our control group has made similar reports and this may be primarily due to the "mentally taxing" nature of the battery of neuropsychological tests administered. This observation provides encouragement for the future use of this system with the elderly and with neurologically impaired groups.

Regarding generalization issues, it appears that for low scorers on the MRT pretest (scores less than 20 out of a possible forty), the VRSR condition produces higher gains on the post MRT compared to practice effects in the control group on this second administration of the equivalent form MRT (mean =+ 9.3 for VE vs. + 2.3 for controls). This result was significant ($p < .05$) with the 19 participants in this subset of our sample. However, this observation needs to be interpreted with caution as it is derived from an early exploratory analysis on a small number of participants. Statistical tests of significance on the other questions outlined above are now being conducted on our data set. Following data analysis of these samples, and contingent upon the continued minimal occurrence of side effects, we will begin running a normal elderly (age 65+) group through the system. Again, following side effect and data analysis of the aged sample, persons with Alzheimer's disease, and a brain injury group will be tested. It is hoped that this measured approach to applying VE technology to these groups will lead to the development of safe, new, and useful assessment, diagnostic, and rehabilitation strategies. The complete results of our first study will be available at the time of presentation to the conference.

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