2006-190: DEVELOPING A VIRTUAL REALITY-BASED SPATIAL VISUALIZATION ASSESSMENT INSTRUMENT

Nathan Hartman, Purdue University

Nathan Hartman is an Assistant Professor in the Department of Computer Graphics Technology at Purdue University, and he has been an ASEE member since 1997. He currently teaches or has taught courses in introductory engineering graphics, 3D solid modeling, 3D surface modeling, and engineering design graphics standards and documentation. Nathan also teaches graduate courses in the foundations of graphics in technology and instrumentation and measurement in research design. He also serves as Graduate Coordinator for the Computer Graphics Technology Department. He has worked for a variety of companies in using and integrating CAD tools in the engineering design process through the development of custom training applications and materials. His current academic interests include the use of constraint-based CAD tools in the design process, the development of expertise in the use of computer graphics tools, spatial visualization ability, and the development of graphic science as a discipline. Nathan holds a Bachelor of Science in Technical Graphics and a Master of Science in Technology from Purdue University, and a doctorate in Technology Education from North Carolina State University.

Patrick Connolly, Purdue University

Patrick Connolly is an Associate Professor in the Department of Computer Graphics Technology with Purdue University at West Lafayette, Indiana. He received his BS degree in Design and Graphics Technology and MS degree in Computer Integrated Manufacturing from Brigham Young University. Prior to joining Purdue in 1996, he worked for twelve years in the aerospace and computer software industries. His interests include solid modeling applications, virtual reality, visualization techniques, learning styles, e-enterprise, and distance learning. He is active in ASEE/EDGD and is a member of the Gamma Rho Chapter of the Epsilon Pi Tau.

Jeffrey Gilger, Purdue University

Jeffrey W. Gilger (PhD, UCSB) is Professor and Associate Dean for Research in the Purdue University College of Education. As Associate Dean he works to build research programs, infrastructure and faculty development mechanisms, and consults or advises on a large number of research projects from very diverse content areas. Gilger’s background includes an MS and certification in Clinical Child/School Psychology, and he holds an MA and PhD in Developmental Psychology with a specialty in Behavioral Genetics. Gilger’s scholarship is multidisciplinary spanning the clinical, educational and neuroscience disciplines. His teaching and research has tended to focus on normal and abnormal neuropsychological development, genetics, and the etiology of learning-language disorders.

Gary Bertoline, Purdue University

Gary R. Bertoline Associate Vice President for Discovery Resources at Purdue University where he plays a significant role in the strategic planning, development, and support of high performance computing, visualization, and research collaboration between Purdue’s IT staff and faculty. Recent projects include the reorganization and expansion of the high performance computing area and led the creation of the NSF funded Envision Center for Data Perceptualization and the Rosen Center for Advanced Computing. Prior to his current position he served as department head for seven years of Computer Graphics Technology at Purdue University. He has authored numerous papers in journals and trade publications on engineering and computer graphics, CAD, and scientific visualization. He has extensive experience in the development of computer graphics curricula and has authored and co-authored eight textbooks in the areas of computer-aided design and engineering design graphics.

Developing a Virtual Reality-based Spatial Visualization Assessment Instrument

Abstract

The computer graphics profession, particularly the educational component, takes into account a person's spatial abilities as a means for designing effective instructional experiences and assessments. Typical assessments examine such abilities as mental rotations, spatial visualization, and spatial perception. Spatial visualization skills relative to a cutting plane passing through an object is critical in the use of in many computer graphics software tools. This ability is widely considered to be a significant predictor of probability of a person's success in the computer graphics vocation. The Mental Cutting Test (MCT) is an assessment instrument that is commonly used to measure spatial visualization skills. This instrument is currently available only in paper-and-pencil format. However, the nature of the human ability being measured is such that the paper-and-pencil format currently used has no mapping to the target construct domain – namely 3D computer graphics in the real world. This lack of authenticity puts into serious question not only the perceived validity (face validity) of the test, but also the purposes for which test scores from the MCT are put to use (construct validity). In an effort to minimize these issues, the cognitive psychology and computer graphics communities have developed virtual reality-based versions of a mental rotations instrument to examine various constructs. But a mental rotations assessment does not provide a complete coverage of a person's spatial abilities. This paper focuses on the development and methodology for pilot testing a working prototype of a virtual reality-based version of a spatial abilities assessment instrument which uses the MCT as a model.

Introduction

Many tasks in our modern world require the ability to perform spatially – to be able to navigate and manipulate objects in the imagined environments of the mind. Many professions and educational entities take into account a person's spatial abilities as a means for designing effective instructional experiences and assessments. In many cases, this has involved the use of a standardized test to measure the spatial aptitude of the participant, followed by the use of the score on that test to predict the level of participant success in a particular setting or vocation. Typical assessments (e.g., the mental Cutting Test (MCT) or the Mental Rotations Test (MRT)) examine such constructs as mental rotations, spatial visualization, and spatial perception. However, these assessments are generally given in paper-and-pencil formats, which are lacking when compared to the 3D tangible worlds individuals must work in.

Standard paper-and-pencil assessment instruments used to measure spatial abilities are inadequate for modern applications and technological capabilities. The use of more realistic and interactive virtual reality (VR) environments would better simulate real world conditions and provide a truer measure of spatial acuity. The focus of this research is the development of a virtual reality-based assessment instrument. This should be completed early in the Spring semester, 2006. Subsequently, we will conduct a pilot study using Purdue students. The purposes of this study are to: a.) to assess the usability of the virtual reality-based assessment (VRBA) instrument and obtain feedback for modifications; b.) conduct a first look at how and if the instrument correlates with more standard devices now used in the field; and c.) to ascertain at this initial phase whether and to what degree the VRBA distinguishes among groups or people in terms of ability and other performance parameters. In doing so, this study will compare paper- and VR-based test results for students from different college majors (engineering and non-engineering) based on their performance on differing versions of the Mental Cutting Test (paper-based and VR-based).

Engineering Graphics and the Need for Examining Spatial Ability

Researchers indicate that without spatial ability, success within specific disciplines can be limited. These areas include the sciences, engineering, the arts, sports, and many other areas[1]. The notion of spatial ability developed from research areas related to psychology and intelligence, and it denotes a relationship between spatial ability and other abilities related to speech and reasoning. However, at the same time, it does make a distinction between them[2, 3]. In fact, Rizzo et. al.[4] and Deno[5] comment that success in higher levels of mathematics and engineering and the design of products respectively, in addition to common daily tasks, are all affected by a person's ability to mentally manipulate objects.

Spatial ability research indicates that there are three (3) related but specialized factors associated with the spatial ability construct. While space prevents a thorough discussion, these factors have been identified by several authors: Mental Rotations, Spatial Visualization, and Spatial Perception[6, 7, 8, 9, 10]. Abilities in each of these factors have been identified as being very important for disciplines, such as engineering and technology. It is also apparent that in some situations it may be possible to improve the spatial ability of students, and this spatial ability is at the heart of the visual learning paradigms suggested by Gardner[12] and West[13].

There is a call for better measures of spatial skills and methods for improving spatial ability. While there are a limited number of studies that examine the effect of training on spatial ability, some have proposed that spatial ability has a biological basis; however, individual differences in the ability are also reflective of environmental input. For instance, Miller and Bertoline[14] suggest that spatial ability develops over periods of time and is related to stages of a person's development and various learning environments and types of life experiences. It has been hypothesized that it is, in part, through these experiences that individuals tend to migrate towards certain career paths, ultimately influenced by their past experiences and the reinforcement they have received for appropriate performance surrounding acknowledged norms of their respective discipline.

One such discipline is computer graphics, specifically the learning and use of contemporary 3D computer-aided design (CAD) tools[16,17]. What further confounds the use of these tools, and is at the heart of the engineering design graphics community's interest in spatial abilities is the quest for virtual space. Duff[18] suggests that 80% of students in engineering graphics classes cannot "see" (partially or entirely) the third dimension that is implied during the creation of an orthographic projection and the corresponding conjure of a mental image. However, it is this phenomenon that is at the very core of the issue being examined in this study – the ability to manipulate virtual space inside a contemporary CAD system and the means by which to measure or assess that ability. These tools not only require the ability of the user to mentally rotate and translate an object, they also require the user to be able to mentally "dissect" the object they are trying to create into its constituent features. These features are derived from, and typically created by, the addition of three-dimensional form to a previously sketched two-dimensional cross section[19]. If a user cannot generate these two-dimensional cross sections (either mentally or digitally), they will struggle in their use of such design tools.

Indeed, spatial visualization abilities play a key role in the effective use of these tools[20, 21], as well as other computer graphics tools that utilize the rotation, translation, and orientation of geometry. The creation of a solid model inside a contemporary sketcher-based CAD system is not the mechanistic process that is used to create an engineering drawing, devoid of the creation of virtual space[22]. It is by default an exercise in the creation and manipulation of virtual space, because unlike the 2D medium of the drawing paper, the default viewing environment of most contemporary CAD systems simulates a 3D environment which the user is immersed in from the initial stages of geometry creation. It is because of this default 3D environment and the inherent use of 2D cross sections to generate geometry, along with the 3D nature of human spatial ability and its tie to success in engineering design, that this study has been undertaken.

Computer graphics educators have considered the research on individual differences in visual-spatial abilities as a means to explain difficulties that students have with geometric representation techniques and methods, especially 3D geometry projection onto 2D planes[23, 24]. Computer graphics educators have also drawn conclusions from research on visual abilities as a means to explain a student's knowledge of 3D space. Visual abilities (and the tests to measure them) have been used as a means to predict or explain success (or lack thereof) in the use of computer graphics tools, likely due to its use of an artificial 3D space[25,26,27,28,29,30]. Wiley[31], Miller[32], and Sexton[33] all suggest that these properties of spatial ability can be embedded into a curriculum that promotes a holistic understanding of engineering graphics techniques, tools and processes. Examining the development of visualization in the context of engineering graphics and CAD tool usage is a natural fit given the propensity of students with high visual abilities to study engineering and technology disciplines[34].

In addition, these examinations of student abilities have typically used a rotations-based instrument to assess spatial ability. However, the paper-based visualization assessment instruments (specifically those dealing with mental rotations and mental cutting or dissection processes) are lacking in their ability to assess a spatial, yet perceptual, construct such as visualization. Traditional measures used for the assessment of mental rotation have produced intriguing findings, but they lack the precision needed to better understand this spatial ability. The most common mental rotations testing scenario involves the use of two-dimensional stimuli (pictorial or perspective line drawings) that portray three-dimensional objects and requires complete mental processing of the stimuli without any motoric involvement[35]. Virtual environments have exhibited the potential to address these flaws and have been used to examine several aspects of human mental faculties: memory, executive functions, spatial skills, motoric components, and attention processes[36].

Psychological Background for Spatial Ability

Spatial ability as a component of human intelligence has been considered by cognitive psychologists for many years. Work by such development pioneers as Piaget, Thorndike, Lowenfeld, and others is routinely cited by researchers as they attempt to situate their studies within established theoretical boundaries[37,38,39]. However, often more challenging than establishing the foundational framework for such empirical work is the task of actually defining what is meant by the phrase ‘spatial ability.’ Strong and Smith[40] made the claim that there are many definitions often applied to this term, and that spatial ability is often interchangeably used with descriptors such as visualization and spatial visualization. Others synonymously used spatial skills[41], spatial intelligence[42], and spatial visualization ability[43]. Velez, Silver, and Tremaine[44] related spatial ability to those “skills involving the retrieval, retention and transformation of visual information” (p. 512).

Early work related to intelligence lead to the emergence of three factors that characterized spatial ability: an ability to discern an object when viewed from alternate angular orientations (S1); the ability to discern elements of an object which are moving or do not remain in their original position (S2); and using one’s own body orientation to address inaccuracies in determining spatial orientation (S3) [45].Researchers that study spatial issues also disagree on the key components or sub-factors that constitute spatial ability. There has been a history in cognitive psychology that there are three primary factors involved in quantifying spatial ability, as well as several sub-factors. According to Eliot and Smith[46], a multitude of paper-based tests were developed during early periods of spatial research, which examined many different influences on spatial ability, including gender, age, learning style, and environment. From these early tests, it became apparent that gender and environment do have some effect on the development of spatial ability Geary and Gilger[47]; Gilger and Ho[48]; Geary[49].

The ability of visualizing three-dimensionally in the mind’s eye has been cited by many authors as a key indicator of educational and career success in many fields. Due to the nature of the topical content, engineering and technology professions are frequently highlighted as professional areas requiring spatial ability[50, 51,52,53,54]. However, researchers have pointed out several other careers that require spatial ability and comprehension, such as architecture, design, piloting, air traffic control, science, mathematics, medicine, and computers[55,56,57]. Furthermore, Smith et al.[58] noted that the ability to spatially visualize is a clear indicator of educational performance in many design and technical graphics courses. Quaiser-Pohl[59] also pointed out the long history of spatial ability as a major aspect of many intelligence models, tests, and theories. Kaufmann[60] stated that “spatial abilities present an important component of human intelligence” (p. 2).

There is some debate among researchers as to the innate nature of spatial ability, and whether and how such skills can be developed (e.g., Geary[61]). Although some cognitive scientists feel that spatial visualization cannot be improved, many practitioners in education and industry claim that this ability can be increased. Sorby[62] differentiated between spatial ability (innate in a person prior to training) and spatial skill (learned or achieved through training). Saito, Suzuki, and Jingu[63] proposed that courses in descriptive geometry and engineering graphics seemed to improve spatial skills. Field[64] also supported the use of freehand drawing (sketching) in courses to enhance spatial visualization skills, while Kaufmann[65] felt that the main purpose of geometry instruction is to improve students' abilities in spatial comprehension. Smith, et al.[66] stated that "visualization is a skill that can be learned, developed, and improved with proper instruction and methods" (p. 16). Strong and Smith[67] felt that while it has not been validated that spatial ability can be taught in a classroom, there is support for such skills being enhanced by experiences in work environments.

There is a significant amount of variance in the general population regarding spatial ability. For example, Velez et al.[68], Tsutsumi, Ichikawa, and Kadowaki[69], Sorby[70], and Makino, Saito, Shiina, Suzuki, & Jingu[71] noted the difference in spatial abilities of males and females. Sorby[72] commented that there are many theories as to why spatial abilities of women seem to lag behind men, including genetic differences and development experiences. Strong and Smith[73] noted spatial ability differences by gender, but additionally claimed that spatial skills can vary by age, individual differences, and life experiences. It is also fairly well accepted that such skills can be developed through a variety of approaches and methods, and that there are considerable differences in spatial ability among the general population. Some of these differences can be noted by categorical distinctions such as gender, age, life experiences, and other individual differences. It would seem then, that spatial ability is a key indicator of performance and success in various sectors of cognitive research, education, and a broad range of professional careers. In this current study, the main focus will be on the aspects of mental rotation (orienting an object in 3D space) and mental cutting (mental transformation of an object affected by a defined cutting plane).

Testing Spatial Ability

A wide variety of tests and assessment instruments have been used in spatial ability testing since research in this area began. Branoff[74] and Sorby[75] described a representative sample of these, including the Purdue Spatial Visualization Test – Visualization of Rotations, the Group Embedded Figures Test, the 3Dimensional Cube Test, the Mental Rotations Test, the Revised Minnesota Paper Form Board Test, and the Differential Aptitude Test. There are many others. Rizzo et al.[76] noted that such tests of spatial visualization skills are often used in cognitive research, brain studies, and central nervous system dysfunction analysis. Although new versions of spatial ability tests are occasionally created (e.g. Quaiser-Pohl[77]), much research has been carried out using traditional paper-based assessments such as the Mental Cutting Test (MCT), a subset of the College Entrance Examination Board (CEEB) Special Aptitude Test in Spatial Relations[78, 79, 80, 81, 82]. The MCT will be the assessment instrument that will be considered in the current study.

The Mental Cutting Test (MCT) is made up of 25 questions, each consisting of a given perspective view of a solid object and a cutting plane to cut the object at some orientation. Participants are required to select from five options, the correct cross section of the resultant cut object. Tsutsumi et al.[83] and Tsutsumi et al.[84] commented on the shape recognition factors that participants experience in MCT problems, including overall impression of object shape and characteristic feature shapes within objects that uniquely qualify object type. Suzuki et al.[85] divided the 25 MCT problems into two categories: problems that require the user to identify the "pattern" of the cross section (overall shape), and problems that require identification of the pattern as well as the "quantity" of the section, meaning the lengths of feature edges and/or angles between feature edges. There are 19 pattern problems and six pattern/quantity problems on the MCT. This would seem to parallel closely with Juhel's[86] assessment that "spatial relations" (require rotational movement of objects) and "visualization tasks" (require transformations on internal features of objects) are key factors involved in overall spatial ability. According to Suzuki et al., a four-step process is involved in solving MCT problems: 1) comprehend the object and cutting plane, 2) cut the object with the plane, 3) rotate the cut object, and 4) recognize and select the correct cross section from the possible solutions. Saito et al.[87] later revised these steps to include identifying the quantity in the cross section after the rotation step. Analysis by Saito et al. clarified that MCT errors rarely occurred in the first step. They noted that more than 70% of recorded error occurred during the second and third steps of the process (cutting and rotating the object). Just fewer than 30% of errors were due to the quantity identification step in the process. For this study, analysis will be done on a virtual reality version of the MCT using the aspects of pattern and quantity as factors.

The MCT has been determined to be a valid measure of various aspects of spatial ability. Sorby[88] claimed that spatial skill ratings based on MCT results were effective in measuring ability to successfully interact with computerized 3D environments. She also provided evidence that MCT results accurately reflected spatial improvements in men and women following engineering graphics course instruction[89]. Makino et al.[90] tracked eye patterns and compared verbal descriptions of problem solving with MCT problems, concluding that the MCT accurately reflects ability in mental imaging. Adenez and Velasco[91] used Item Response Theory with the Rasch model to validate the MCT as an acceptable spatial ability measure. Using the pattern and pattern/quantity differentiation described above, the authors determined that MCT had construct validity in measuring spatial abilities. Sugai and Suzuki[92] also supported the construct validity of the MCT through exploratory factor analysis methods.Reliability analysis of the MCT was carried out by Magin and Churches[93] using Kuder-Richardson Formula 20 and Formula 21 methods. Results on pre- and posttest and test-retest data showed high and consistent reliability scores of .80 or higher for all comparisons.

Spatial Ability Testing and Virtual Reality

Virtual reality (VR) is a broad and encompassing term that includes many aspects of computer-generated environments and subsumes various levels of immersion, such as desktop VR, semi-immersive or augmented VR, and fully immersive VR[94]. Bryson[95] described VR as an "interface paradigm that uses computers and human-computer interfaces to create the effect of a three-dimensional world in which the user interacts directly with virtual objects" (p. 62). Some researchers[96, 97, 98] considered VR from a fully immersive, completely artificially created, multi-sensory paradigm, while others[99, 100] examined the virtual experience from an augmented perspective – a combination of artificial and existing environments. Feedback to the user can vary in both of these scenarios. Some augmented or immersive contexts are visual-feedback only, while some may include audio or haptic response[101]. The anticipated context for this study will be a fully immersive, completely artificial environment, with visual-only sensory feedback to the user.

The uses for virtual reality are also many and varied. Smith and Lee[102] reported many applications in the design and manufacturing industries for virtual mockups and product design verification. VR has proven to be effective for industrial, military, and other training applications[103]. Meehan et al.[104] reported VR activity in psychological treatment such as post-traumatic stress cases and phobia intervention, and Rizzo et al.[105] indicated potentially major impacts of VR in neuropsychological assessment and cognitive rehabilitation. Velez et al.[106] stated that VR technology is being adopted in such diverse fields as scientific visualization, medical applications, industrial applications, information display, and airport security.

To this point in time, virtual reality applications in education are scattered and minimal, but promising. Topic areas such as geometry, mathematics, science, and engineering have all been reported successful in VR educational settings, as have spatial ability and visualization skill development[107, 108, 109]. Besides practical topic instruction assistance, VR promises to benefit learners in more intangible ways. Student motivation, social interaction, and collaboration (especially in distance education scenarios) can be impacted by this technology[110, 111]. Fällman[112] also noted that VR may benefit educators by allowing for physical impossibilities to be modeled and displayed. These might include changes to users' size relative to objects, artificial sensory cues to indicate information or situational changes, and representation of objects with no form in the physical world in order to make abstract knowledge tangible. Hindrances to VR applications in the classroom include technological and economic challenges, training, hardware and software roadblocks, lack of sufficient empirical data to support VR inclusion, and user/VR interaction issues such as cyber sickness and other immersive impacts[113, 114, 115, 116]. The overall outlook for VR impact in education is positive and will no doubt increase rapidly. Passig and Sharbat[117] reported:

> According to . . . experts, the use of VR in education can be aimed to provide more attractive, motivating, and much more interesting learning experiences to future students. [Experts] would like to see the novelty, the immersion, the stimulation of the senses, and the feeling of exploration encouraging the student to move from passive learning to active learning. Most of all, they would like to see VR technology supporting the cooperative learning environment we all strive for. (p. 11)

While some virtual reality testing of spatial abilities has been accomplished, such research generally has centered on rotational tasks and instruments. Preliminary research has shown that not only might VR remove some inherent biases in paper-based tests (male/female differences among high and low visualizers, 2D assessment of a 3D ability, and the ambiguity of isometric illustrations in 2D instruments), but also that VR instruments may be more effective in truly measuring spatial ability[118, 119, 120, 121]. The MCT has specifically been identified as a promising VR development area[122]. The potential for 3D spatial ability testing in actual (artificial) 3D environments is a natural outgrowth of technological and information advances in both the fields of spatial ability assessment and virtual reality. In order to further empirical research in virtual reality and its impact on spatial ability development, an immersive VR version of the Mental Cutting Test (MCT) will be developed and tested. It is proposed that such an instrument would overcome many of the limitations that hamper current paper-based MCT assessments.

Methodology

In order to compensate for the ambiguities and imperfections inherent to traditional spatial visualization assessment methods, a new battery of instruments is necessary – one that more accurately examines the mental faculties called upon in the use of contemporary computer graphics tools. It is our contention that this can be done by developing a virtual reality-based battery of assessments that include the constructs of spatial visualization and dissection of geometry. This would correspond to the operational mechanisms inherent to many contemporary computer graphics tools. To accomplish this goal, a prototype of a virtual reality-based assessment (VRBA) instrument will be developed. It will utilize a similar research design as that employed by Rizzo et. al.[123] and Alpaslan et al.[124], except the comparison will be between the paper-based version of the test and the virtual version of the same or similar test.

It is noteworthy that the planned VRBA tests will provide a wealth of unique data and cognitive/performance measurements not available through more standard spatial assessments. For example, we hope to design a VRBA instrument that will capture these performance indices: a.) overall correctness of response; b.) response times for overall response as well as per each move and completion of component steps; c.) the degree of movement of pieces in 3D space as the individual approaches the problem, correctly or incorrectly; and, d.) a graphic depiction of the process of problem solving over time. Each of these parameters can be analyzed towards a complete picture of the individual's errors and correct steps.

Research Questions

First, can a virtual reality-based assessment instrument be developed that is *at least* as effective in measuring visualization and 3Dimensional comprehension as traditional spatial visualization assessment methods? Second, how do engineering and non-engineering students perform on the paper-and virtual reality-based versions of the Mental Cutting Test (MCT)?

Design

This study will involve virtual reality technology in an attempt to compare paper-based and virtual reality-based versions of a spatial ability instrument. To that end, an immersive virtual environment and VR testing instrument will be created. The pilot study and initial survey results will provide corrective information for the VR instrument and procedures, as well as assisting in determination of the needed number of participants for a larger follow-up study. Table 1 outlines the basic design for this study. This study is a 2 (Student Major) by 2 (MCT Format) factorial design[125].

Participants

The participants for this study will be 60 Purdue University freshmen and sophomores from the Colleges of Education and Engineering. The undergraduate population at the university is representative of Midwestern universities in general, and care will be taken to fully describe the participants' demographic characteristics. Thirty students from each of the two majors will be ascertained voluntarily through advertisements on campus. All 60 participants will receive the paper-based and the virtual reality-based version of the MCT prototype. Data from interviews and questionnaires, as well as GPAs will also be collected. These data will be used to identify areas of needed refinement of the VRBA, as well as serve as some post-hoc and statistical covariates in our analyses. Subjects will be paid for their participation. Appropriate IRB procedures will be followed including informed consent.

Instruments

Three instruments will be used in this study. The first is the existing paper-based version of the Mental Cutting Test (MCT) (See Appendix A for complete instrument). The MCT contains 25 problems requiring the participant to select from five options the correct cross section resulting from a planar cut through the representation of a 3D object. In order to determine the correct response, participants must mentally manipulate the object to visualize the resultant cross section. A sample problem from the MCT is shown in Figure 1.

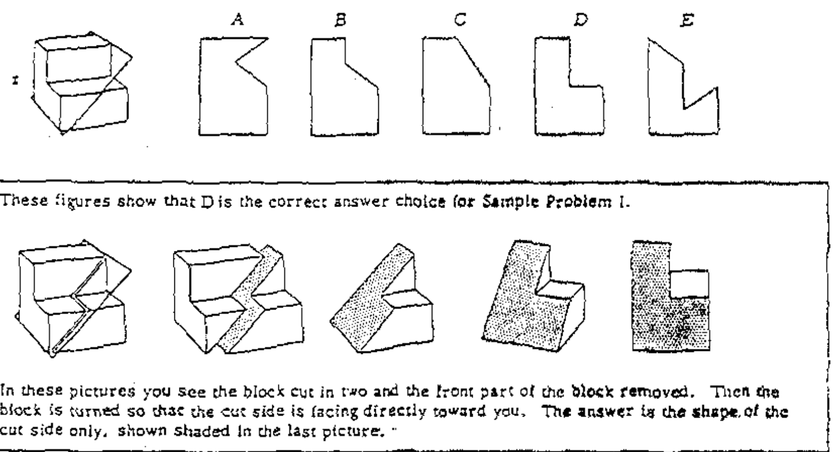

Figure 1. Mental Cutting Test Sample Problem

As mentioned previously, the MCT is appropriate for measuring the spatial ability factors of mental imaging and spatial visualization[126, 127]. The work of Adanez and Velasco[128], Saito et al.[129], and Sugai and Suzuki[130] specifically address the construct validity of the MCT using Item Response Theory, error analysis, and exploratory factor analysis, respectively. The reliability of the paper-based MCT was examined in depth by Magin and Churches[131]. They reported Kuder-Richardson formula 20 values (proportion of participants passing and failing each item) for MCT posttest scores for students in five different classes ranging from .86 to .89. KR21 values (using mean scores and variances) for pretest and posttest scores for the same five classes ranged from .82 to .88.

The purpose of this study is to assess the effectiveness of a virtual reality-based version of the MCT. This second instrument, the VRBA currently under development, will be utilized to measure the spatial ability of students in an immersive 'CAVE' environment. Figures 2 and 3 shown below depict the layout and selection options for the VRBA. At this stage of the research, the participant will simply have stereoscopic vision in a passive environment. No interaction with the object will be allowed in an attempt to establish a baseline measure of the effects of stereoscopic vision on a person's MCT score. The participant will be outfitted with active stereoscopic glasses and a control wand for locating the position of the hand. A view of each MCT problem will be shown to the participant, and five possible answers will be given. They will be asked to select the correct answer from the choices given. Each problem of the VRBA matches the corresponding problem on the paper-based MCT in terms of the object shown, the orientation of the view, and the position of the cutting plane. The participant will not be allowed to rotate, pan, or zoom in and out on the model, as is the case on the paper-based MCT. By directing the locating vector to the appropriate response (A, B, C, D, or E) and depressing a button on the control wand, a participant is able to select their desired answer.

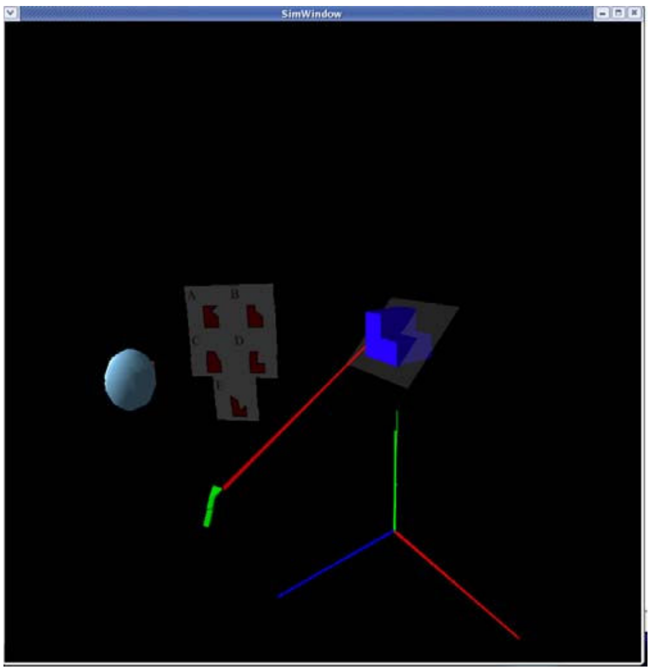

Figure 2: Layout of a Sample VRBA Test Problem

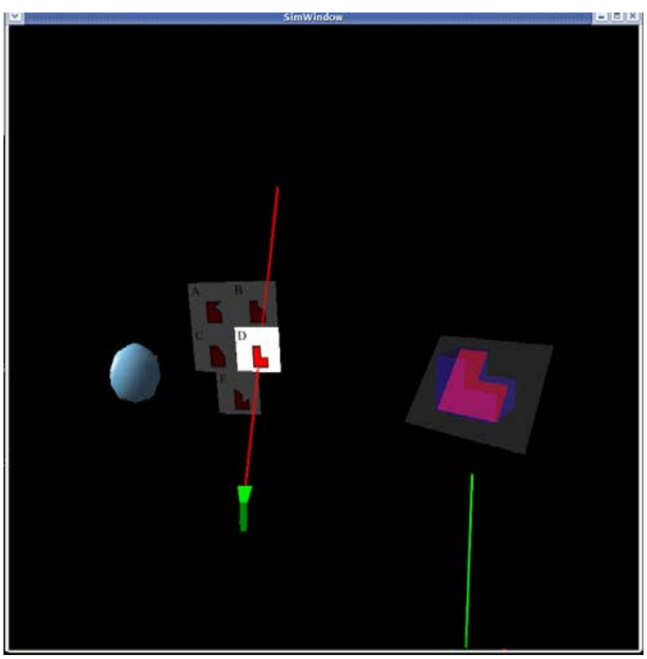

Figure 3: Answer Selection within the VRBA Environment

A third set of instruments will be used to collect demographic information about the participants regarding age, academic class, academic major, GPA, SAT score, computing experience, life experiences, and other pertinent information.

Procedures

Initially, an immersive virtual environment will be developed utilizing the technological capabilities of the Envision Center at Purdue University. This environment will be established in the 3D CAVE domain, providing projections to three walls and floor of the test area and creating an immersive effect for the participants. Additionally, a virtual reality version of the Mental Cutting Test (MCT) will be created to act as the testing instrument. These two steps (currently in process for the environment creation) will occupy significant lead time in programming and pretesting operations.

All subjects will become familiar with the testing procedures and tasks. Half of each student major group will take the paper-based MCT version first, followed by the immersive VR version. The other half of each major group will take the VR version first followed by the paper-based version.

For each test, data will be collected as to the number of items answered correctly, and which items were missed for each participant. Time to complete the tasks will also be recorded. Upon completion of the spatial tasks, participants will be asked to complete a survey that will gather information on perceived benefits and shortcomings of the environment, instruments, and potential side effects such as cyber sickness[132, 133].

Demographics questions asked of subjects will include both Likert scale quantitative measures and open-ended response questions. All paper-based testing will occur under standardized methods and under researcher observation. Participants will have 20 minutes to complete the 25-question MCT. Virtual reality-based testing will have automatic score recording via computer response instruments under participant control. Data from all tests will be entered into a storage database for analysis and safekeeping. Survey results will be tabulated, coded (where necessary), and cross-checked for accuracy.

Data Analysis

Because this is a pilot study and instrument development project, statistical issues like power are not critical at this time. Moreover, for the VRBA instrument it is difficult at this juncture to identify power properties such as expected effect size and reliability. However, prior work in the area of spatial ability testing has found effects and been successfully published with sample sizes of this size and fewer (reviewed in Geary[134]). Prior to any inferential analyses, the distributional properties of the data will be examined and outliers will be removed and/or normalization processes will be applied if needed. Our general primary analysis is a 2x2 Mixed Analysis of Variance (ANOVA) of the test error rates and correct response rates. There is one between Ss factor, major type, and one within Ss factor, test type. This analysis will yield main effects for test type, Ss major type, and a test type by Ss major type interaction. Secondary analyses of test performance will later include the response time data, and other dependent variables available.

The survey or interview data, and GPA data will be used to inform the researchers as they VBRA instrument is further developed. Some of these data will also be used as covariates in some of the analyses planned (e.g., GPA or age).

Anticipated Outcomes

While there are many questions regarding how VR technologies may impact educational strategies, it is hoped that the results of this study will highlight significant areas of focus that can be leveraged to improve education approaches, curricular issues, and at-risk student methodologies. Another potential contribution may involve testing approaches utilizing current and emerging technology. Lastly, it is hoped that the results of this study will lead to other studies in many related and similar areas to further the impact of this technology in educational practices.

The anticipated outcomes of this project fall into two categories: the development of the virtual assessment environment and the actual examination to participants. It is anticipated that a satisfactory virtual environment can be developed with the existing facilities at the Envision Center for Data Perceptualization at Purdue University. The virtual environment will be similar to those created by Rizzo et al.[135] and Alpaslan et al.[136] in that it will pass through a development and refinement phase relative to the experimental population chosen.

For the initial pilot stage of the VRBA development, it is anticipated that there will be no significant differences between participants' scores on the VRBA and the paper-based MCT. As described in the Instrument section above, this could be attributed to the close parallel between the VRBA and the paper-based MCT. If so, it may be possible to state that the VRBA is at least as effective as the paper-based MCT at measuring spatial visualization ability. Further study will involve manipulation of the VRBA to allow for greater levels of immersion and interactivity within the VR assessment environment. It is anticipated that differences between the VRBA and the paper format will be seen at that time.

With respect to the future testing environment and the pilot test itself, it is anticipated that there will be significant differences in scores on paper-based assessments versus virtual-based assessments. The hope is that these differences can be attributed to the ability of the virtual environment to track the orientations and translations that the participant goes through to determine the proper cross-section of a given object (and a series of mental rotations/orientations as time permits). The hope of the authors is that they will be able to determine the mental progression that the participant goes through to determine when they have achieved the correct cross-section for the given object when passing a virtual cutting plane through the given virtual object.

It is anticipated that the results will show significant differences between the results for paper-based tests between the engineering and non-engineering students. This would be consistent with previous research done in this field. It is assumed that there will also be differences between the virtual reality-based results for engineering and non-engineering students. This will help validate the virtual reality-based assessment instrument. This could indicate a preference for either the VR-based instrument or paper-based instrument, and/or indicate the relative effectiveness of one version of the instrument over another and lead to further studies related to these questions. Given that this study is in progress, data were not available for analysis at the time of this writing. However, it is anticipated that preliminary results will be available for presentation at the 2006 Annual Meeting of the American Society for Engineering Education.

References

1. Deno, J. A. (1995). The relationship of previous experience to spatial visualization ability. *The Engineering Design Graphics Journal, 59*(3), 5-17.
2. Pellegrino, J., Alderton, D., & Shute, V. (1984). Understanding spatial ability. *Educational Psychologist, 19 (*3), 239-253.
3. Eliot, J., & Smith, I. M. (1983). *An International Directory of Spatial Tests*. Highlands, New Jersey: Humanities Press, Inc.
4. Rizzo, A., Buckwalter, J.G., Larson, P., van Rooyen, A., Kratz, K., Neumann, U., Kesselman, C., & Thiebeaux, M. (1998). Preliminary findings on a virtual environment targeting human mental rotation/spatial abilities. *Proceedings of the 2nd European Conference on Disability, Virtual Reality and Associated Technologies. Skovde, Sweden, 1998.*
5. See Ref. 1
6. Smith, I. M. (1964). Spatial ability, its educational and social significance. San Diego, CA: Robert R. Knapp.
7. See Ref. 3
8. Olson, D. R., & Bialystok, E. (1983). A theory of spatial representation. In D. R. Olson & E. Bialystok (Eds.), *Spatial Cognition: The Structure and Development of Mental Representations of Spatial Relations.* (pp. 233-259). London: Lawrence Erlbaum Associates.
9. Linn, M. C., & Petersen, A. C. (1986). A meta-analysis of gender differences in spatial ability: Implications for mathematics and science achievement. In J. S, Hyde & M. C. Linns (Eds.), *The psychology of gender: Advances through meta-analysis* (pp. 67-101). Baltimore, MD: Johns Hopkins University Press.
10. Verderhus, L., & Krekling, S. (1996). Sex Differences in Visual Spatial Ability in 9-Year-Old Children. *Intelligence, 23*, 33-43.
11.
12. Gardner, H. (1993). *Multiple intelligences: The theory in practice.* New York: Basic Books.
13. West, T. G. (1997). *In the mind's eye*. Amherst, NY: Prometheus Books.
14. Miller, C. L., & Bertoline, G. R. (1991). Spatial visualization research and theories. *The Engineering Design Graphics Journal, 55 (3),* 5-14.
15.
16. Hartman, N.W. (2004). The development of expertise in the use of constraint-based Computer graphics tools: Examining practicing professionals. *The Engineering Design Graphics Journal, 68* (2), 14-25.
17. Hartman, N.W. (2005). Defining expertise in the use of constraint-based CAD tools by examining practicing professional. *The Engineering Design Graphics Journal, 69* (1), 6-15.
18. Duff, J. M. (1979). Visual perception: The problem of creating visual space. *Engineering Design Graphics Journal, 43*(2), 42-43.

19. Saitz, R. (2005). Parametric modeling history. Retrieved from http://www.mcadonline.com/index.php?option=com_content&task=view&id=177&Itemid=73on December 15, 2005.
20. Branoff, T. J. (1998). The effects of adding coordinate axes to a mental rotations task in measuring spatial visualization ability in introductory undergraduate technical graphics courses. *The Engineering Design Graphics Journal*, 62 (2), 16-34.
21. Branoff, T. J. (2000). Spatial visualization measurement: A modification of the Purdue Spatial Visualization Test - Visualization of Rotations. *The Engineering Design Graphics Journal*, 64 (2), 14-22.
22. See Ref. 20
23. Roorda, J. (1994). Visual perception, spatial visualization and engineering drawing. *The Engineering Design Graphics Journal, 58*(2), 12-21.
24. Devon, R., Engel, R. S., Foster, R. J., Sathianathan, D., & Turner, G. F. (1994). The effect of solid modeling software on 3-D visualization skills. *The Engineering Design Graphics Journal, 58*(2), 4-11.
25. Sorby, S.A. (1999). Developing 3-D spatial visualization skills. *The Engineering Design Graphics Journal, 63*(2), 21-32.
26. Sorby, S.A. (2000). Spatial abilities and their relationship to effective learning of 3-D solid modeling software. *The Engineering Design Graphics Journal, 64*(3), 30-35.
27. Sexton, T. J. (1992). Effect on spatial visualization: Introducing basic engineering graphic concepts using 3-D CAD technology. *The Engineering Design Graphics Journal, 56*(3), 36-43.
28. See Ref. 14
29. Miller, C.L. (1992). Advocating the development of visual perception as a dominant goal of technical graphic curricula. *The Engineering Design Graphics Journal, 53*(1), 27-38.
30. See Ref. 1
31. Wiley, S. E. (1989). Enhancing visual literacy of engineering students through the use of real and computer generated models. *The Engineering Design Graphics Journal, 56*(1), 1-11.
32. See Ref. 29
33. See Ref. 25
34. See Ref. 1
35. See Ref. 4
36. See Ref. 4
37. Magin, D. J., & Churches, A. E. (1994). Reliability and stability of two tests of spatial abilities. *Proceedings of the Sixth International Conference on Engineering Computer Graphics and Descriptive Geometry, Tokyo, Japan,* 801-805.
38. See Ref. 29
39. See Ref. 25
40. Strong, S., & Smith, R. (2001). Spatial visualization: Fundamentals and trends in engineering graphics. *Journal of Industrial Technology, 18*(1), 1-13.
41. Gorska, R., Sorby, S. A., Leopold, C. (1998). Gender differences in visualization skills – an international perspective. *Engineering Design Graphics Journal, 62*(3), 9-18.
42. Kaufmann, H. (2003, February). *Collaborative augmented reality in education.* Paper for keynote speech at Imagina 2003 conference, Monaco.
43. See Ref. 1

44. Velez, M. C., Silver, D., & Tremaine, M. (2005). Understanding visualization through spatial ability differences. *Proceedings of Visualization 2005. IEEE, Minneapolis, MN, USA,* 511-518.
45. Thurstone, L. L. (1950). *Some primary abilities in visual thinking.* Chicago, IL: University of Chicago Psychometric Lab Report No. 59.
46. See Ref. 3
47. Geary, D.C., & Gilger, J.W. (1989). Age of sexual maturation and adult spatial ability. Bulletin of the Psychonomic Society, 27, 241-244.
48. Gilger, J.W., & Ho, Hsiu-Zu. (1989). Gender differences in adult spatial ability: Their relationship to pubertal timing, adolescent activities, and sex-typing of personality. Cognitive Development, 4, 197-214.
49. Geary, D.C. (1998). Male-Female: The evolution of sex differences. Washington, DC: APA Books
50. See Ref. 1
51. Field, B. W. (1999). A course in spatial visualization. *Journal for Geometry and Graphics, 3*(2), 201-209.
52. See Ref. 37
53. See Ref. 40
54. See Ref. 44
55. Adanez, G. P., & Velasco, A. D. (2002). Predicting academic success of engineering students in technical drawing from visualization test scores. *Journal of Geometry and Graphics, 6*(1), 99-109.
56. See Ref. 1
57. See Ref. 18
58. Smith, S., Taylor, K., Green, T., Peterson, N., Garrety, C., Kremis, M., & Thompson, A. (2005). Using virtual reality tools in design and technical graphics curricula: An experience in learning. *Engineering Design Graphics Journal, 69*(1), 16-25.
59. Quaiser-Pohl, C. (2003). The mental cutting test "Schnitte" and the picture rotation test—two new measures to assess spatial ability. *International Journal of Testing, 3*(3), 219-231.
60. See Ref. 42
61. See Ref. 49
62. See Ref. 25
63. Saito, T., Suzuki, K., & Jingu, T. (1998). Relations between spatial ability evaluated by a mental cutting test and engineering graphics education. *Proceedings of the Eighth International Conference on Engineering Computer Graphics and Descriptive Geometry, Austin, TX, USA,* 231- 235.
64. See Ref. 51
65. See Ref. 42
66. See Ref. 58
67. See Ref. 40
68. See Ref. 44
69. Tsutsumi, E., Ichikawa, A., & Kadowaki, N., (2001). Evaluation of mentally perceived differences between the 3D objects used in mental cutting tests. *Journal for Geometry and Graphics, 5*(1), 101-109.
70. See Ref. 25

71. Makino, K., Saito, T., Shiina, K., Suzuki, K., & Jingu, T. (1992). Analysis of problem solving process of a mental cutting test by the use of eye fixations data. *Proceedings of the Fifth International Conference on Engineering Computer Graphics and Descriptive Geometry, Melbourne, Australia,* 398-402.
72. See Ref. 25
73. See Ref. 40
74. See Ref. 21
75. See Ref. 25
76. See Ref. 4
77. See Ref. 59
78. Saito, T., Makino, K., Shiina, K., Suzuki, K., & Jingu, T. (1994). Causes of error in a mental cutting test – analysis of problem solving process by the use of eye fixations data(2). *Proceedings of the Sixth International Conference on Engineering Computer Graphics and Descriptive Geometry, Tokyo, Japan,* 815-819.
79. See Ref. 63
80. See Ref. 25
81. Suzuki, K., Shiina, K., Makino, K., Saito, T., Jingu, T., Tsutsumi, N., Kashima, S., Shibata, M., Maki, H., Tsutsumi, E., & Isoda, H. (1992). Evaluation of students' spatial abilities by a mental cutting test. *Proceedings of the Fifth International Conference on Engineering Computer Graphics and Descriptive Geometry, Melbourne, Australia,* 277-281.
82. See Ref. 69
83. Tsutsumi, E., Shiina, K., Suzaki, A., Yamanouchi, K., Saito, T., & Suzuki, K. (1999). A mental cutting test on female students using a stereographic system. *Journal for Geometry and Graphics, 3*(1), 111-119.
84. See Ref. 69
85. See Ref. 81
86. Juhel, J. (1991). Spatial abilities and individual differences in visual information processing. *Intelligence, 15*, 117-137.
87. See Ref. 78
88. See Ref. 26
89. See Ref. 25
90. See Ref. 71
91. See Ref. 55
92. Sugai, Y., & Suzuki, K. (1999). Comparison of problem solving process between a mental cutting test and other spatial tests. *Proceedings of the Fourth China-Japan Conference on Graphics Education, Dunhuang, China,* 105-110.
93. See Ref. 37
94. Fällman, D. (2000). *Introduction to VR in education.* Retrieved November 25, 2005, from Umeå University, Department of Informatics Web site: http://www.informatik.umu.se/~dfallman/projects/vrie/intro.html
95. Bryson, S. (1996). Virtual reality in scientific visualization. *Communications of the ACM 39*(5), 62-71.
96. Edwards, G. W., Barfield, W, & Nussbaum, M. A. (2004). The use of force feedback and auditory cues for performance of an assembly task in an immersive virtual environment. *Virtual Reality, 7,* 112-119.

97. Meehan, M., Insko, B., Whitton, M., Brooks, F. P., Jr. (2001). Physiological measures of presence in virtual environments. Proceedings of the 4th Annual International
98. Smith, S, S-F, & Lee, S-L. (2004). A pilot study for integrating virtual reality into an introductory design and graphics course. *Journal of Industrial Technology, 20*(4), 2-7.
99. See Ref. 42
100. Szalavari, Z., & Gervautz, M. (1997). The personal interaction panel – a two-handed interface for augmented reality. Computer Graphics Forum 16(3), C335-C346.
101. See Ref. 96
102. See Ref. 98
103. Stanney, K. M., Kingdon, K. S., Graeber, D., & Kennedy, R. S. (2002). Human performance in immersive virtual environments: Effects of exposure duration, user control, and scene complexity. *Human Performance 15*(4), 339-366.
104. Meehan, M., Insko, B., Whitton, M., Brooks, F. P., Jr. (2001). Physiological measures of presence in virtual environments. Proceedings of the 4th Annual International Presence Workshop, Philadelphia, PA, 1-28.
105. See Ref. 4
106. See Ref. 44
107. Kaufmann, H., & Schmalstieg, D. (2002). Mathematics and geometry education with collaborative augmented reality. *Computers & Graphics 27*(3), 339-345.
108. See Ref. 98
109. See Ref. 58
110. See Ref. 42
111. See Ref. 58
112. See Ref. 94
113. See Ref. 95
114. See Ref. 42
115. See Ref. 58
116. See Ref. 103
117. Passig, D., & Sharbat, A. (2001). The why and how VR in schools: A preferred future pedagogic mission by a group of worldwide experts in VR and education. *International Journal of Virtual Reality, 5*(1). Retrieved September 1, 2005 from http://www.passig.com/pic/VRInSchool.htm
118. See Ref. 107
119. See Ref. 40
120. See Ref. 83
121. See Ref. 12
122. See Ref. 12
123. See Ref. 4
124. Alpaslan, Z. Y., Yeh, S.C., Rizzo, A.A., & Sawchuk, A.A. (2005). Quantitative comparison of two stereoscopic three-dimensional computer interaction methods. *Proceedings of the. Stereoscopic Displays and Virtual Reality Systems XII Symposium, Vol. 5664, San Jose, CA, 2005.*
125. Gall, M. D., Gall, J. P., & Borg, W. R. (2003). *Educational research: An introduction* (7th ed.). Boston: Allyn and Bacon.
126. See Ref. 71
127. See Ref. 92

128. See Ref. 55
129. See Ref. 63
130. See Ref. 92
131. See Ref. 37
132. See Ref. 96
133. See Ref. 103
134. See Ref. 49
135. See Ref. 4
136. See Ref. 124