Annual Report for Period: 07/2009 - 06/2010

Principal Investigator: Kaber, David
Organization: North Carolina State U

Submitted By:
Kaber, David - Principal Investigator

Title:
HCC: Medium: Haptic Simulation Design for Motor Rehabilitation and Skill Training

Project Participants

Senior Personnel

Name: Kaber, David

Worked for more than 160 Hours: Yes
Contribution to Project:
Dr. David Kaber is a professor of industrial and systems engineering (ISE) at North Carolina State University (NCSU). He has worked as the principal investigator on the project over the past year. He has coordinated the efforts of the project subteams at NCSU and Duke University, including: integrating virtual reality (VR) systems and haptic devices to support motor skill rehabilitation intervention research; conducting a cognitive task analysis (CTA) on diagnosis and rehabilitation processes for minor Traumatic Brain Injury (mTBI) cases; reviewing literature on neuropsychological tests for modeling in VR; reviewing literature on functional limitations of persons with mTBI; and planning a first experiment to assess the utility of VR and haptic-based rehabilitation strategies for improving non-dominant hand motor skills in able subjects. Kaber has directed and supervised six graduates students working on the project.

Name: Lee, Yuan-Shin

Worked for more than 160 Hours: Yes
Contribution to Project:
Dr. Yuan-Shin Lee is a professor of industrial and systems engineering (ISE) at NCSU. He has worked as a co-principal investigator on the project, directing research assistants dividing their time between the Computer-Aided Design Lab and Cognitive Ergonomics Lab. These persons included Yingjie Li and Manida Swangnetr. Lee has provided the students with guidance on the design of haptic device and control software integration. He has also participated in presentations of the VR system and haptic device setups for visitors to the ISE Department.

Name: Tupler, Larry

Worked for more than 160 Hours: Yes
Contribution to Project:
Dr. Larry Tupler is Assistant Professor of Medical Psychology in the Department of Psychiatry and Behavioral Sciences at Duke University Medical Center (DUMC) and Director of the Neurocognition Laboratory of the Mid-Atlantic Mental Illness Research, Education, and Clinical Center (MIRECC), headquartered at the Durham Veterans Affairs Medical Center (VAMC). In the first year of the project, Dr. Tupler led the Durham team by recruiting Dr. Karen Tucker to replace Dr. Jasmeet Pannu-Hayes, who was listed on the original grant application but relocated to Boston University and the Boston VAMC and thus could not oversee fMRI activities anchored in Durham, NC. (She is willing to advise the project in the future upon completion of data collection.) Tupler also recruited three additional scientific collaborators: two with substantial expertise in fMRI and apparatus development (Dr. Jeff Brownadyke of the Alzheimer’s Disease Research Center and Dr. Jim Voyvodik of the Brain Imaging and Analysis Center of DUMC) and one with occupational-therapy expertise from the Durham VAMC (Nan Verbel) to advise on the cognitive task analysis (CTA) portion of the study concerning motor-skills training undertaken by NCSU. He engaged in protocol development and procurement operations to consolidate the fMRI
apparatus. Tupler also served as an expert neuropsychologist to provide input to the NCSU CTA on neuropsychological practice and assisted the NCSU team to further advance the science and engineering underlying the interface between human sensory-motor systems and the VR-haptic apparatus that is the principal technology developed within the current effort. Finally, Tupler has planned a fMRI experiment to assess the impact of VR-based motor skill training during the second year of the research project.

**Name:** Tucker, Karen  
**Worked for more than 160 Hours:** No  
**Contribution to Project:**  
Dr. Karen Tucker is a clinical and research neuropsychologist at the Durham VAMC with an adjunct faculty appointment at DUMC. She has assisted the team by contributing to the design and planning portion of the fMRI experiment and participating in the NCSU CTA portion of the study concerning neuropsychological assessment of TBI in recently returning war veterans serving in Afghanistan and Iraq. She has made initial preparations to assist with fMRI data processing to derive blood oxygenated level-dependent (BOLD) activation maps in response to subtractive comparisons arising from contrasting instructional sets.

**Graduate Student**  
**Name:** Clamann, Michael  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**  
Michael Clamann is a full-time PhD is ISE at NCSU. During this past year, he served as the project director for the Cognitive Ergonomics Lab subteam through a half-time research assistantship. Michael planned the CTA on mTBI case diagnosis and rehabilitation processes with David Kaber. Michael led the task analysis, including interviews with expert technicians at the Durham VAMC. He directed the design and prototyping of the physical workstations for VR display and haptic device presentation. He also coordinated the development of the VR system software platforms and integration of the 3D stereoscopic displays with haptic devices. He has conducted a separate literature review on cognitive and physical implications of mTBI. Finally, he has defined the conditions and laid-out the procedures for the first VR-based motor skill rehabilitation study to begin in Summer 2010. Michael will take the ISE PhD qualifying exam this summer.

**Name:** Li, Yingjie  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**  
Yingjie Li was also a full-time PhD student in ISE. She served as co-director of the Cognitive Ergonomics Lab subteam through a quarter-time research assistantship. She conducted a literature review on haptic-based VR for motor-skill training. She was also responsible for setting-up the VR hardware and programming software to deliver an electronic version of the Rey-Osterrieth Complex Figure (ROCF) Test (a neuropsychological test for motor disability diagnosis). Yingjie developed a system to automatically recognize ROCF components in patient reproductions and to score accuracy, etc. She also designed and developed versions of the task to facilitate rehabilitation of motor control and planning skills for users. Yingjie also participated in the CTA on mTBI diagnosis and rehabilitation processes, conceptual design of VR tasks for the first experiment, and planning of the experimental study with Michael Clamann. Yingjie completed her doctoral dissertation research in May of 2010 and will graduate in August. She was directed in her research by David Kaber and Yuan-Shin Lee. Larry Tupler also served as one of her dissertation committee members.

**Name:** Jeon, Wooram (Linus)  
**Worked for more than 160 Hours:** Yes
Contribution to Project:
Linus Jeon is a full-time PhD student in ISE. During this project year, he worked as an hourly employee (for 10 hrs./wk). Linus was responsible for setting-up the software platforms for delivering VR-based task simulations. He also worked on prototyping neuropsychological tests in VR. Beyond this, Linus worked on ensuring the compatibility of various operating systems with VR development toolkits as well as integrating stereoscopic display technologies and several haptic devices with the VR simulations. His main focus has been on the interoperability of haptic devices with 3-D VR displays.

Name: Swangnetr, Manida
Worked for more than 160 Hours: Yes

Contribution to Project:
Manida Swangnetr is also a PhD in ISE. She worked as a half-time research assistant to Yuan-Shin Lee and David Kaber on the project. Her focus has been on identifying functional limitations associated with mTBI and drawing correspondences with functional limitations in non-dominant hand use. Manida defended her dissertation proposal in May of 2009 and plans to graduate in Summer 2010.

Name: Zhang, Yu (Zeno)
Worked for more than 160 Hours: Yes

Contribution to Project:
Yu (Zeno) Zhang is a PhD student in ISE. During this past year, she worked as a quarter-time research assistant to David Kaber. (She was also supported through the Ergonomics Center of North Carolina.) Zeno participated in design of physical workstations for presenting VR displays to users and providing access to haptic devices. She also was responsible for conceptual design and storyboarding of VR implementation of a block matching and positioning task. This task was considered as a candidate task for the first experiment on VR-based motor skill training. Zeno passed the ISE PhD qualifying examine in May 2010.

Name: Zhu, Biwen
Worked for more than 160 Hours: Yes

Contribution to Project:
Biwen Zhu is a PhD student in ISE. During this past year, he worked as a quarter-time research assistant to David Kaber. (He was also supported through the Ergonomics Center of North Carolina.) Biwen worked on material specification and assembly of prototype physical workstations for presenting VR displays and haptic devices to users. He setup a workstation integrating a Novint Falcon device. He also worked with Manida Swangnetr on reviewing literature concerning motor impairments for TBI patients as well as motor control and planning issues for non-dominant hand use. Biwen made comparison of motor characteristics between TBI patients and non-dominant hand users. Biwen passed the ISE PhD qualifying examine in May 2010.

Undergraduate Student
Technician, Programmer
Other Participant
Research Experience for Undergraduates
Organizational Partners
Duke University Medical Center
Dr. Jeff Browndyke is an assistant professor in the Department of Psychiatry of DUMC. He has
collaborated with Dr. Tupler on the planning and development of the fMRI protocol for this project. He performs clinical- and research-neuropsychology work within the Byran Alzheimer's Disease Research Center at DUMC. He is affiliated with the Brain Imaging and Analysis Center (BIAC) at DUMC.

Duke Institute for Brain Sciences
Dr. Jim Voyvodik is an assistant professor in the Department of Radiology, faculty in the Duke Institute for Brain Sciences, and affiliated with the BIAC. He has collaborated with Dr. Tupler on the project to develop the fMRI apparatus, based on his prior work with camera-lucida and other methods of stimulus presentation within the MRI suite.

Durham VA Medical Center
Ms. Verbel is an occupational therapist at the Durham VAMC. She has advised the project team on the principles of occupational therapy for the benefit of the CTA specification of rehabilitative techniques for sensorimotor rehabilitation of TBI.

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
(Please see attached file)

Findings: (See PDF version submitted by PI at the end of the report)
(Please see attached file)

Training and Development:
The training opportunities that resulted in association with the activities of the ISE subteam included:

(1) graduate student (Swangnetr and Zhu) learning on physical and cognitive deficits associated with TBI and how such limitations may parallel limitations in non-dominant hand performance by unimpaired individuals;
(2) graduate student (Clamann) learning on physical workstation design to accommodate presentation of neuropsychological tests, including the ROCF reproduction task;
(3) graduate student (Li and Zhang) learning on methods of conceptual and electronic task prototyping for validation of potential strategies to VR-based rehabilitation of motor skills;
(4) graduate student (Clamann, Jeon and Li) training on integration of stereoscopic display technologies and haptic devices with high-performance graphics workstations for VR presentation;
(5) graduate student (Jeon and Li) training on virtual environment modeling and interactive scenegraph development through Visual C++, VESS and OpenGL programming; and
(6) graduate student (Jeon and Li) training on development of haptic rendering algorithms as part of VR applications through OpenHaptics programming.

Related to these training opportunities, Yingjie Li completed here Ph.D. dissertation on an automated scoring system for the ROCF reproduction task. She will graduate from NCSU in August of 2010. She is currently interviewing for researcher positions with companies.
The publications generated by the ISE subteam, including study of surgical simulator fidelity and human performance, may serve as guide for the design and development of VR-based simulations for motor skill assessment and development. The research also provides insight into the tradeoff of simulation fidelity with system responsiveness and the impact on user behavior. The results are useful from the perspective of determining what level of visual fidelity to provide for a sense of realism in the simulation without compromising user interactivity and motor learning due to rendering lags. In addition to this research, the ISE subteam publication on comparison of haptic devices for computer-based assessment of motor control abilities provides guidance on what types of technologies are most effective for achieving muscle activation patterns in drawing that are comparable to pen and paper task performance. This is critical to generalization of VR-based motor training to real-world tasks. Finally, the team publication on haptic-based virtual environment design for assessing motor skills in pathological populations presents an approach to the design and development of hardware and software systems for automating complex neuropsychological testing. The approach may be adopted by others conducting similar research.

Outreach Activities:
The NCSU ISE subteam has nothing to report on outreach activities at this time.
The DUMC subteam has nothing to report on outreach activities at this time.

Journal Publications


Books or Other One-time Publications


Li, Y., "Development of a Haptic-based Rey-Osterrieth Complex Figure Testing and
Training System with Computer
Scoring and Force-feedback
State University, Raleigh, NC USA.

Web/Internet Site

Other Specific Products

Product Type:
Software (or netware)

Product Description:
Virtual ROCF (Rey-Osterreith Complex Figure)?

Sharing Information:
The ISE subteam developed a Visual C++ software application simulating the Rey-Osterrieth
Complex Figure (ROCF) reproduction task for neuropsychological assessment. The software
supports haptic device integration for patient drawing of figures and automated scoring of
results. The task is to be used in first year experiment for subject baseline motor skill
performance assessment and for post-therapy testing. (The software will be made accessible
through the research project website to be developed during the second project year.)

Contributions

Contributions within Discipline:
The activities of the ISE subteam have served to advance industrial engineering, specifically
in the area of human factors. Little prior research has investigated approaches to user-
centered design of VR-based simulations for motor control skill development. We
developed an approach to integration of stereoscopic displays, haptic control devices and
physical worktables for presenting simulations of neuropsychological tests. We also
applied an established CTA (cognitive task analysis) methodology for identifying
information requirements of expert neuropsychologists and occupational therapists in
motor skill diagnosis and rehabilitation procedures. On the basis of the CTA results, we
selected several existing psychomotor performance tests for prototyping in VR and
presentation through the new workstations. The objective of this work was to create
platforms for automated diagnosis procedures and for empirical study of the effectiveness
of VR-based motor control therapy regimens. Beyond this, the research team proposed a
novel experiment design to quantify the psychomotor performance effects of different
therapy regimens integrating visually and haptically enhanced VR simulations.

The results of our research on development of a VR-based surgical simulator and the
effects of levels of simulation fidelity on VR system responsiveness and user motor
behavior have been submitted to the International Journal of Human-Computer Studies.
The results of our research on the design and development of a VR-based version of the
ROCF reproduction task and automated scoring system were published through the 2010
Computer-Aided Design and Applications Conference.

Contributions to Other Disciplines:
All of the research findings of the NCSU ISE and DUMC subteams are expected to
contribute to the disciplines of neuropsychology and rehabilitation. The ISE subteam
activities during the current year included a review of TBI (traumatic brain injury) research
and comparison of physical and cognitive implications of TBI with non-dominant hand

capabilities of unimpaired persons. This review is expected to have value for researchers working in neuropsychology and rehabilitation as it draws parallels between motor behaviors of pathological and unimpaired populations. It provides a basis for study of unimpaired persons in order to gain insight into characteristics of TBI.

With respect to the research by the DUMC, the new apparatus developed for psychomotor task performance during fMRI tests is expected to be generally useful for research on associating brain responses with motor skill requirements. The setup provides a basis for linking motor planning and control activities to specific blood flow patterns in the motor cortex, as revealed through MRIs.

Contributions to Human Resource Development:
This project is providing specialized training for the ISE graduate students in engineering design through the development of VR workstations for supporting neuropsychological testing of patients with TBI. The students have also learned how to apply CTA methods to the study of motor skill diagnosis and rehabilitation, including interviewing SMEs on treatment of pathological populations for physical and cognitive deficits due to TBI. The students are also honing their skills in VR simulation prototyping and experiment design, as well as conducting technical literature reviews. In general, it is expected that this training will improve student performance as research assistants at NCSU and will support development of advanced research skill sets for work in the rehabilitation engineering industry or academia.

Contributions to Resources for Research and Education:
With respect to contributions to institutional resources for research, in this project year the grant supported acquisitions of new high-performance graphics workstations, stereoscopic display technologies and haptic control devices for the Cognitive Ergonomics Lab. This equipment will be used not only in the planned project experiments, but also in student dissertations directly related to the grant. This has already occurred in the case of Yingjie Li’s dissertation study. Project equipment, including a Dell Precision 530 workstation and the SensAble Phantom Desktop haptic device, were integrated to support presentation of the V-ROCF reproduction task and for conducting user performance testing. Recently, the project grant supported purchase of an additional SensAble Omni haptic device for use with the Dell XPS 420 workstation (already present in the Cognitive Ergonomics Lab) and the WAIS-III test battery. In order for the team to develop virtual prototypes of the Block Design and Matrix Reasoning subtests as part of the WAIS, it was necessary to acquire the physical form of the tasks through the commercial market. The physical tasks will also be used with certain subject groups in the first year experiment, as described in the Findings section.

Contributions Beyond Science and Engineering:
The Virtual ROCF system developed as part of this research has significant commercial potential. The software has the capability to: (1) present the original ROCF stimuli; (2) support patient reproduction using tablet or haptic control devices; (3) perform automated drawing component recognition; and (4) perform automated drawing result scoring for clinicians. In general, the system substantially automates many steps in use of the ROCF for motor skill assessment and disability diagnosis for TBI patients. The system may be useful to VA hospitals throughout the country and other healthcare facilities treating patient populations with brain injuries and associated motor skill disabilities. At this point in time, NCSU plans to make the V-ROCF system an ‘open source’ project accessible to all users through the Internet in order to accelerate enhancements of extensions of the system.

All of the VR-based prototypes of existing psychomotor performance tests to be developed by the project team for experimental research purposes are expected to have commercial technology potential. Such applications may have utility in neuropsychology and rehabilitation practices, in general.

Conference Proceedings
Special Requirements

Special reporting requirements: None
Change in Objectives or Scope: None
Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Any Web/Internet Site
Any Conference
ACTIVITIES

[NCSU Subteam]

During the first year of the project, the industrial and systems engineering (ISE) team at NCSU (Kaber, Lee, Clamann, Li, Jeon, Swangentr, Zhang and Zhu) pursued several objectives, including:

(1) acquiring new hardware for presentation of high-end and consumer-grade three-dimensional (3D) environments with haptic control;
(2) interviewing subject matter experts (SMEs) on motor skill diagnosis and rehabilitation procedures, as a basis for informing haptic simulation design and configuration;
(3) identification of various virtual reality (VR)-based strategies for supporting motor skill learning in order to optimize speed and transfer of training to real tasks;
(4) development of prototype VR tasks to guide the rehabilitation system development effort;
(5) development of a first year experiment plan incorporating unimpaired subjects for data collection;
(6) set-up of a new rehabilitation workstation and development of code libraries to create a functional prototype of a block design task; and
(7) reviewing literature on neurological systems used for touch sensations as well as comparisons of motor skill tests.

[DUMC Subteam]

During the first year of the project, the subteam in Durham, NC pursued the formulation and implementation of fMRI experimentation and apparatus. This work is to facilitate neuroimaging of brain regions mediating the component processes of drawing constructional praxis and changes in performance and BOLD activation with motor-skill training delivered through VR-haptic-device training.
FINDINGS

[NCSU-ISE Subteam]

Activity (1)

The ISE subteam made several hardware acquisitions for VR system development and presentation of rehabilitation task simulations. A Dell Precision 5500 desktop was acquired and equipped for complex visualizations and graphics rendering. The 5500 was set-up and tested with all the necessary drivers and development libraries to support higher end VR environment and haptic control hardware devices, including a StereoGraphics 3D emitter and SensAble Phantom® Desktop (haptic) device.

A Dell XPS 420 desktop was also set-up as a secondary system to support the higher end consumer-grade hardware acquired for the study. The system was integrated with an nVidia 3D-Vision emitter for VR environment presentation and a Novint Falcon® haptic control. It is expected that software developed for this system by the research team may be more widely distributable due to the greater accessibility of the hardware.

The ISE research team partnered with NC State's Furniture Manufacturing and Management Center to construct a custom workstation for presentation of the Rey-Osterrieth Complex Figure (ROCF) task (see Figure 1.1). The workstation features a 19-inch LCD monitor embedded flush with the worktable surface and slot for fixed placement of a haptic control. The control is positioned on the worktable in order to overlap the viewable area of the monitor.

![Figure 1.1. Custom workstation for presentation of electronic versions of neuropsychological tests.](image)
The visual display as part of the station serves as a writing surface for the haptic device. Users are able to “write” on the monitor directly with the Phantom haptic device stylus. Key advantages of the new workstation include easy and consistent setup and visibility of task stimuli under a variety of lighting environments.

**Activity (2)**

The ISE subteam conducted a series of interviews with SMEs in motor skill diagnosis and rehabilitation. Experts included Drs. Larry Tupler and Karen Tucker, neuropsychologists at the Durham Veterans Administration Medical Center (VAMC), and Ms. Nan Verbal, a collaborator on the project and occupational therapist (OT) at the Durham VAMC. The interviews were conducted as part of a cognitive task analysis (CTA) to identify information requirements of medical professionals responsible for diagnosing and rehabilitating patients with a history of TBI (traumatic brain injury). The results of the CTA were also expected to drive the design of the virtual environments for rehabilitation task simulation. Such simulation should not only support patient skill development but also yield performance outcomes that clinicians can use in the rehabilitation process.

Interviews with the neuropsychologists were conducted during three separate sessions. The overall goal of the sessions was to identify how patient’ conditions are evaluated after an initial screening and how clinicians determine whether a patient has a history, including TBI. The results of the interviews were summarized in a high-level goal-directed task analysis (GDTA) format. This methodology identifies task goals, sub-goals, specific objectives and task steps (see Figure 2.1).

The GDTA begins with identification of the goal to respond to a referral or question regarding a patient. Subgoals include evaluating composite medical data on patients, analyzing the results of tests and interviews with the patient and diagnosing their condition. Recommendations on therapy and rehabilitation are often made jointly with a rehabilitation expert.

During the interviews with the rehabilitation subject matter expert, the research team learned how an OT develops customized interventions for patients with a history of TBI. Typically, patients want to improve performance in specific daily motor tasks and this is a major factor in definition of the therapy. The OT interviews revealed that motor impairments resulting from TBI and the interventions used to overcome them could be highly variable. Interventions are generally customized for the needs of each patient, which adds to the challenge of designing a suite of VR tools that will apply to the greatest population of patients.

The results of the rehabilitation interviews helped determine that the best course of action for developing VR environments for supporting motor skill diagnosis and rehabilitation would be a collaborative, iterative process in which the ISE subteam proposes a prototype and the SMEs provide feedback to drive design improvements. Prototype enhancements
would be reevaluated by the SMEs. This process would be expected to continue until all stakeholders were satisfied with the results.

Activity (3)

On the basis of the CTA research, the ISE subteam also identified various strategies to the design of VR-based rehabilitation regimens. The variables defining strategies include:
(a) the type of test task;
(b) enhancements of the task through VR (beyond what is possible in the real-world form of the test); and
(c) the duration of task exposure as well as the number of therapy sessions.

Neuropsychological Test for Prototyping in VR

From the proposal, the ROCF was considered as a candidate task for simulation in VR. The Figure stimulus is standardized and includes drawing elements that allow for assessment of patient motor planning skill and praxis (i.e., ordering or sequencing of elements and
determination of necessary hand posture positions), as well as control capability in reproduction. Other advantages of the ROCF include standardized approaches to drawing scoring with clear rule sets that can be coded in a computer program. However, the ROCF task is most conducive to supporting motor control diagnosis procedures and may less applicability for skill rehabilitation.

In addition to the ROCF, various components of the Wechsler Adult Intelligence Scale (WAIS) battery, including the Block Design and Matrix Reasoning tasks, were considered for inclusion in therapy regimens. These tasks impose basic spatial reasoning and motor control requirements on patients. The simple nature of the tasks allows for ease of replication in VR and administration to patients. Standardized scoring methods also exist for the Block Design and Matrix Reasoning tasks. One drawback of the tasks is the abstract content may limit generalizability of skill development to real world tasks that a patient wants to achieve through rehabilitation.

**VR-based Enhancements to Existing Psychomotor Tests**

Some enhancements to these candidate tasks, which are possible through haptic controls and VR simulation, were formulated. In ROCF reproduction using a haptic device, it is possible to provide force-assistance to guide patients in drawing elements in a desired direction. Figure 3.1 shows a model of the force assistance mode. The equation describing the guiding force is: \( F_a = s \cdot q \). \( F_a \) is a force for directing the drawing on the designed trajectory. \( s \) is the strength of the force, which is a constant, set as a system parameter. \( q \) is a vector defining the direction along with the trajectory. (This vector can be generated from a database.) At any time \( t \) during the drawing process, the patient will be led by the force \( F_a(t) \) in the direction \( q(t) \).

![Figure 3.1. Force-feedback assistance model.](image)

Another mode of assistance in the ROCF reproduction task is to place a force constraint on the haptic device based on the position of the cursor in the drawing space within the virtual environment. \( F_a(t) \) can be defined as the drag force on the virtual cursor at the closest point to the desired drawing trajectory: \( F_a(t) = 0, \) if \( d = 0 \) and \( d \neq 0 \). Here, the force strength is constant and \( d \) is the vector to the closest point on the designed trajectory.

A third mode of haptic force feedback assistance in the ROCF task is to set virtual grooves along desired drawing trajectories (see Figure 3.2) for patients to follow with a cursor.
during the Figure reproduction. The center point of the groove is the cross-section of the designed trajectory for copying, and the dashed lines are two virtual walls along the boundaries of the trajectory. The virtual walls only exist on the virtual drawing surface adjacent to the trajectory. Patients can move the control point along the drawing trajectory without feeling any obstacles; however, if copying deviates from the defined trajectory, patients can feel the virtual walls and cannot penetrate the walls without lifting the pen. The width (w) of the groove is a parameter defining the distance between the walls that can be controlled through the software. This and the other forms of force-feedback enhancement to the ROCF task through VR simulation are to be prototyped and tested as part of rehabilitation engineering experiments during the course of the research.

![Diagram of the groove for constraining drawing trajectories in ROCF reproduction.](image)

**Figure 3.2. Virtual groove for constraining drawing trajectories in ROCF reproduction.**

In regard to enhancements of the Block Design task through VR simulation, we conceptualized both visual display and force-feedback aiding through haptic device use. Components of the Block Design task include sorting blocks and matching them to a referent pattern for positioning. In order to facilitate block placement in the pattern, visual aids, such as “virtual strings” dangling from blocks, can be rendered to enhance user depth perception and increase accuracy in block placement. In terms of force-feedback assistance, texturing can be applied to specific block surfaces in order to facilitate subject orientation of blocks for placement in patterns and for tracking block position during movement. As with the proposed enhancements for the VR-based version of the ROCF task, the visual and force aids for the block design task are to be prototyped and tested in repeated trials in human subjects experiments.

**Frequency and Duration of Therapy Sessions**

On the duration and number of therapy session to be included in a VR-based motor skill rehabilitation regimen, the CTA with the OT revealed therapy sessions with mTBI patients typically last for about 1 hour and are repeated multiple times per week depending upon patient needs (personal communication with Nan Verbal). The number of sessions is gradually reduced as the patient makes progress in skill development. For our initial empirical study of the VR system and simulations of the ROCF and Block Design tasks, we have planned to include a task training session for subjects, followed by three to four therapy sessions lasting 1 hour each with one session occurring per week. The therapy
sessions are to be followed by a post-experiment test session. Various combinations of the rehabilitation tasks, enhancements through VR, and session frequency and duration are to be tested as part of this research. The ultimate objective is to identify regimens that have the greatest impact on motor skill development as measured by comparing training task and post-experiment test performance.

**Activity (4)**

The ISE subteam designed a first group of VR-based rehabilitation task prototypes based on guidelines developed using the information collected from the CTA as well as follow on literature reviews of studies involving VR environments developed to train motor skills. Early prototypes ranged from paper prototypes (see Figure 4.1) to animated graphic renderings (see Figure 4.2). The team also verified that each prototype would be compatible with the SensAble Phantom® haptic device and some sort of augmented haptic control (e.g., the force assistance or force constraint enhancements to the ROCF task). The results of this effort identified common ground between intervention techniques for training motor skills and the haptic controls. For example, many of the important prehensile grasps used in real-world therapy settings, including lateral, palmar and fingertip, can be translated to the haptic control devices. Minor modifications to device implements can be made to achieve certain types of grasp. However, this can compromise the fidelity of force rendering through the device. Software solutions can also be implemented. For example, in simulating real tasks requiring patients to use tweezers for object grasping or placement, a cursor can be rendered in the VR task space that is capable of applying an attractive bonding force to other objects allowing for transport in the virtual environment, like using a pair of tweezers.

Existing diagnosis tasks that require repetitive use of prehensile grasps that could be adapted using VR were also considered as candidate tasks for prototyping in VR. Use of existing tests, like the ROCF and Block Design Task, is helpful because the tests are fully developed and empirically validated for assessing psychomotor performance and can be replicated as a real-world task.

Beyond the ROCF and Block Design tasks, prototype tasks proposed by the team generally fell in two categories, including shape sorting and stacking. Shape sorting tasks require participants to insert objects into specified target locations (e.g., positive forms into compatible negative forms), like the Block Design Task. Stacking tasks require participants to place items on top of each other in a particular order. Although simple in concept, both are used in evaluating psychomotor performance and can be easily adapted to VR. Other compatible standardized tests include the Purdue Pegboard task and Roeder Manipulative Aptitude task. In general, both shape sorting and stacking tasks allow for additional haptic aiding or interference in an augmented VR environment. This is important because one of the main objectives of this research is to demonstrate the capability of user-centered VR simulation design for accelerating motor skill rehabilitation relative to conventional therapy approaches.
For the empirical study on VR therapy regimen design, the team decided to focus on the Block Design Task of the Third Edition of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler 1997). As previously mentioned, the Block Design Task evaluates visuo-spatial and motor skills. In specific, subjects are required to build replicas of constructions using blocks printed with simple patterns. They are given a collection of nine “red” and “white” cubes with varying patterns on each side and are asked to replicate the patterns shown on a series of test cards. This task was selected for the experiment for several reasons:
• Performance requirements of the Block Design Task are related to the requirements of the ROCF reproduction task (see Spreen & Strauss, 1998). A VR-based version of the ROCF is also to be used in the study as an objective measure of any motor skill training effects resulting from use of the Block Design Task for therapy.
• The Block Design Task is designed to test visual information processing in both impaired and unimpaired subjects. The task is expected to be sensitive to measure performance differences among members of the unimpaired sample to be used in the first year study.
• As described above, the Block Design Task can be adapted to a VR environment and enhanced relative to its real form.

The empirical study design will incorporate the Block Design Task in the therapy sessions. Subjects will perform the task either as a real-world task, a VR task, or an augmented VR task featuring the forms of haptic aiding or interference, as described under Activity (3).

References


Activity (5)

The ISE subteam also developed a study plan for the first year experiment. The objective of this experiment is to design and test VR interfaces for rehabilitation and motor training, using some of the augmented visual and haptic features described above, in terms of learning speed, generalization and transfer to real tasks. We will attempt to validate some forms of VR as a rehabilitation tool by measuring how performance in a motor task may be affected by training with 3D displays and haptic control devices. The overarching goal is to gain insight into how to best present specific functions of a haptic control interface for rehabilitation and skill training applications for persons attempting to recover from mTBI with motor control implications or seeking to train new motor skills for work and societal activities. The study is a preliminary step in the larger research effort to advance the state of VR-based haptic simulation design for such practical applications.

Equipment

The experiment apparatus will include VR simulation of the Block Design and Matrix Reasoning subtests from the WAIS-III and a subset of tests from the ROCF test. We will make use of the custom workstation (described in Activity (1)) for test administration. The VR interface will be presented using a 3D stereoscopic display, active light-shutter goggles and an emitter developed by CrystalEyes and StereoGraphics, accordingly. The haptic
control interface will utilize SensAble Technologies’ Phantom® Desktop™ Haptic Device (Figure 5.1). The Phantom Desktop includes a boom-mounted stylus providing 5 degrees of freedom for movement and 3 degrees of freedom in force feedback.

![Figure 5.1. SensAble Technologies Phantom Desktop](image)

Motor skill tests

As discussed above, the Block Design and Matrix Reasoning subtests from the WAIS-III, and the ROCF, are three commercially available psychomotor performance tests commonly used in vocational and therapeutic settings. In general, the WAIS-III measures intelligence for unimpaired adults. It is composed of 14 subtests that combine to measure different intelligence “factors”, including verbal comprehension, working memory, processing speed and perceptual organization (Kaufman & Lichtenberger 1999). We will only use two of the 14 subtests. The Block Design Task was described in detail in the report on Activity (4) (see Figure 5.2 for an image of the task stimuli).

The Matrix Reasoning subtest of the WAIS III measures visual information processing by requiring subjects to complete patterns appearing in a grid and selecting a single solution from five choices. The subtest includes 26 items of increasing difficulty (Kaufman & Lichtenberger 1999). (The Block Design and Matrix Reasoning subtests are two of three tests comprising a Perceptual Organizational Index (POI) within the WAIS III. The index is a measure of visual motor coordination and nonverbal thinking (Kaufman & Lichtenberger 1999).)

The ROCF reproduction task has also been identified above. Subjects must copy a complex figure both visually and from memory. As previously mentioned, the ROCF and the Block Design Task rely on a “visuo-spatial perceptual/memory factor” and their performance has been shown to be moderately correlated (Spreen & Strauss 1998).
Figure 5.2. The Block Design Task (www.finitegeometry.org)

Subjects

This study will include 21 healthy students as subjects due to availability and to facilitate recruiting of a greater number of subjects (as compared to using a mTBI pathological population). All subjects will be required to be 18 years or older, have 20/20 or better vision (corrected or uncorrected), and have full color vision (due to the stimuli as part of the Block Design Task). All subjects will be required to exhibit left or right hand dominance. Ambidextrous subjects will not be allowed to participate. Since we will not be using patients with a history of TBI, we will require students to use their non-dominant hand to simulate conditions resulting from an injury, such as motor impairment due to TBI or loss of the dominant hand. (Additional rationale for modifying the proposed experiment to include unimpaired subjects is included in the reporting on the literature review (Activity (6)).

Phases of Experiment

Each subject will participate in three phases of experimentation, including:

1. orientation and baseline testing (about 2 hours);
2. motor skill therapy (three sessions of about 1 hour each); and
3. final testing (about 2 hours)

The entire experiment is expected to require approximately 7 hrs. for a subject to complete over the course of several weeks.
In the first phase, baseline non-dominant hand performance will be evaluated using copy and recall tests with the ROCF and the WAIS-III Matrix Reasoning subtest. Use of the non-dominant hand to simulate motor impairment has been investigated in other studies involving unimpaired subjects (Caeyenberghs et al., 2009). The second phase of the experiment will include repeated therapy sessions for subject non-dominant hand motor skill development. This is intended to reduce subject task performance time and reveal differences among specific training conditions. Each subject will receive a total of 3 hours of motor skill therapy across three separate visits (1 hour per visit). During the therapy phase, subjects will be required to grasp, manipulate and place small objects (blocks), either through a physical or VR simulation of the Block Design Task. Half the subjects using the VR-based version of the task will be presented with the visual and force-feedback enhancements through the haptic device, as discussed above. (See Table 5.1 for sequence of experiment conditions for subject groups.) Training time will be consistent across task conditions. Each subject will only receive one type of training for the duration of the experiment. In the third phase, subjects will be retested using the ROCF and Matrix Reasoning subtest to identify any changes from their baseline motor performance.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Testing</th>
<th>Physical Task Training</th>
<th>Basic VR Task Training (no haptic interference)</th>
<th>Augmented VR Task Training (haptic interference)</th>
<th>Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td></td>
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<td></td>
<td>X</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

**Baseline Testing Details**

Subjects will complete copy and recall trials of the ROCF using their non-dominant hand to control a VR adaptation of the test (Li 2007). Following the ROCF tests, subjects will complete the Matrix Reasoning subtest also with their non-dominant hand. Again, ambidextrous individuals will not be permitted to participate in the study. Administration of the Matrix Reasoning subtest will follow the version of the guidelines included in the *WAIS-III Technical Manual* (Wechsler 1997). Following baseline testing, subjects will rate the cognitive demands imposed by the ROCF and Matrix Reasoning tests using the NASA Task Load Index (TLX; Hart & Staveland, 1988). They will rank the importance of various workload demands to the test tasks and rate the level of each demand that they perceived.

**Therapy Session Details**

The first therapy session will occur immediately following baseline testing. The second session will be scheduled a week later and will not include additional psychomotor performance testing. The final therapy session will be scheduled two weeks after the first session and will be followed by another test battery. The form of therapy will depend on
the group to which each subject is assigned. Each therapy session will involve multiple trials lasting approximately 10 minutes each.

The subject groups for the experiment will be as follows:
- **Group 1**: Subjects will receive therapy using a physical form of the task. For this experiment, the physical task will consist of the Block Design Task using the non-dominant hand. Each participant will perform the task once, according to the testing guidelines included in the *WAIS-III Technical Manual* (Wechsler 1997).
- **Group 2**: Subjects in this group will be presented with the basic VR version of the Block Design subtest. As in the traditional version, subjects will be required to arrange a collection of nine virtual cubes to match a series of patterns presented on the screen. Subjects will be timed and scored automatically by the virtual system. Trials will be completed using the non-dominant hand.
- **Group 3**: Subjects will be exposed to the augmented VR version of the Block Design task. They will be presented with visual aids for depth perception, block texturing for enhanced orientation, and some “resistance” when arranging the blocks in a pattern. The resistance will occur among the blocks, making it more difficult to place the blocks next to each other. Resistance will increase as proximity decreases (e.g., magnets of the same polarity).

**Testing Details**

Final testing will be similar to baseline testing, with subjects completing the ROCF copy and recall tests as well as the Matrix Reasoning subtasks with the non-dominant hand. Following testing, subjects will once again complete the NASA TLX subjective workload rating form.

**Experiment Procedure**

The specific steps in the experiment procedure include the following:
1. Completion of an informed consent form.
2. Demographic data collection, including subject name, age, gender and handedness will be recorded. (Any personal information collected through the survey will not be included on any other forms as part of the study.)
3. Completion of baseline testing, including ROCF copy and recall tasks, using the non-dominant hand. Instructions for the ROCF copy and recall trials presented in the *Rey complex figure test and recognition trial* professional manual (1995) will be followed for this testing.
5. Administration of the initial subjective workload index.
6. Task therapy in 1 of the 3 experimental conditions
7. Task therapy in 1 of the 3 experimental conditions, identical to the training condition in Session 2
(8) Task therapy in 1 of the 3 experimental conditions, identical to training condition in Sessions 1 and 2
(9) Completion of ROCF copy and recall tests using the non-dominant hand.
(10) Completion of Matrix Reasoning tests using the non-dominant hand.
(11) Administration of the final subjective workload index.
(12) Completion of the experiment: A researcher will thank the subjects for their time and give them an honorarium.

Items 1 through 6 occur on the same day (Session 1); Item 7 occurs during the second day (Session 2); Items 8-12 occur together on the final day (Session 3).

Hypothesis

We hypothesize participant psychomotor test scores will improve in general, as a result of completing any of the three training conditions. Basic VR training is not expected to exceed traditional physical task training in improving subject motor skills due to the fact that the VR will model the physical task with high fidelity and no additional interference will be developed as part of the VR presentation. However, the augmented VR condition is expected to lead to improved performance due to the visual and haptic enhancements developed beyond the constraints of the traditional training.

Independent and Dependent Variables

The primary independent variable will be the three different therapy regimens, including (1) the physical task condition serving as a baseline; (2) the basic VR condition with additional visual support; and (3) the augmented VR condition with haptic control. Dependent variables will include the scores from the ROCF reproduction task and Matrix Reasoning subtests. Differences will be determined between the baseline and the final test results. The difference of the scores will be regarded as the indication of motor skill improvements after the 3-day therapy regimen. The subjective workload index will be used to assess the cognitive demands of the tests administered during the first and final sessions. The workload ratings will be compared to identify any changes in subject perceptions. No data from the therapy sessions will be analyzed.

Data Analysis

The experiment will follow a single factor, randomized complete between-subject design. “Subject” will be treated as a blocking effect due to the potential for individual differences in performing the tests. The different therapy regimens will be treated as fixed effects in the statistical model:

\[ \text{ROCF}_{\text{dif}} \text{ MR}_{\text{dif}} = \mu + \text{subject} + \text{Type} + \epsilon \]

If the data collected during the experiment do not conform to the distributional assumptions of the ANOVA (Analysis of Variance), non-parametric statistics will be used (e.g. Friedman tests).
References


Activity (6)

The ISE subteam previously developed a computer-based version of the ROCF reproduction task (the V-ROCF), which will be used in the planned experiment. Specifically, the V-ROCF will be used to evaluate baseline and final performance levels that may change as a result of training.

A VR version of the Block Design subtask from the WAIS-III is to be used as the therapy task in the planned experiment. This simulation is currently under development. The goal of the software, called the V-BDT, is to reproduce the Block Design Task in VR as accurately as possible, with the addition of haptic aiding and interference (see the study plan presented as part of Activity (5) for details).

Several preliminary steps had to be completed to facilitate the V-BDT development effort. The team began programming the task using a Dell XPS 420 with a 2.4 GHz Intel® Core™2 Quad CPU. An nVidia GeForce GTX 280 video card and nVidia 3D Vision package were added to the system to present the 3D environment. In December 2009, the ISE subteam acquired a new Dell Precision 5500 for VR development and presentation. This workstation has a 2.26 GHz Intel Xenon (E5520) CPU and 4 GB of RAM. The video card is an nVidia Quadro FX 4800 with 1.5 GB of graphics memory for rendering high-end
visualizations. Although both systems (the XPS 420 and Precision 5500) are capable of presenting the VR environment with haptic control, the Precision workstation is intended to be the flagship VR presentation system.

Microsoft Visual C++ is being used with both workstations for the majority of the development work, including modeling graphical objects, OpenGL programming for graphics, and OpenHaptics (SensAble Phantom Desktop) and Novint library (Novint Falcon) programming for haptic control. The Dell Precision uses the VESS (Virtual Environment Software Sandbox) and the Dell XPS uses nVidia’s software development kit (SDK) for rendering 3D environments. The initial development effort required installing and integrating the hardware (i.e., StereoGraphics emitters and haptic devices), development environments, and existing V-ROCF software.

As some members of the team produced paper-based task prototypes (see Activity (4)), others developed electronic replicas of aspects of the prototypes in elementary VR environments (see Figure 6.1). These interactive prototypes were created to provide additional validation (through testing) of the task design concept and to facilitate development of the code libraries and objects necessary for producing the VR software.

![Figure 6.1. Shape sorting and stacking task prototype.](image)

**Activity (7)**

In parallel with the above activities on VR workstation design and development, VR-based rehabilitation task prototyping and experiment planning, the ISE subteam conducted a literature review on TBI and non-dominant hand performance by non-pathological populations. Traumatic brain injury causes severe impairments in physical and cognitive
function (Khan, Baguley & Cameron 2003). Physical deficits occur in coordination, balance, ambulation, fine motor skill and strength. Deficits in cognitive functions occur in memory, information processing, planning and language. Similar deficits in physical and cognitive functions can also be observed in non-dominant hand use in healthy persons, as compared with dominant hand performance. It stands to reason that research findings on non-dominant hand performance and methods of skill training might provide insights into the capabilities of TBI patients and rehabilitation approaches.

The asymmetric use of the non-dominant compared to the dominant hand results in a relatively decreased dexterity of the non-dominant hand, extensively demonstrated in the literature (Armstrong & Oldham 1999; Ozcan, Tulum, Pinar, & Baskurt 2004). Motor strength is commonly found to be greater in dominant hands. The “10% rule” states that the dominant hand possesses 10% greater grip strength than the non-dominant hand. However, some studies have shown that the 10% rule is valid for right-handed persons only; for left-handed persons, grip strength should be considered equivalent in both hands (Petersen, Petrick, Connor, & Conklin 1989). Many studies (e.g., Schmidt & Toews 1970; Armstrong & Oldham 1999) have found hand strength to be significantly greater in dominant hands for right-handed participants. No significant differences have been observed between dominant and non-dominant hand performance for left-handed participants. A more recent related study also revealed asymmetrical manual performance in grip strength, manual dexterity and pressure pain threshold in right-handed subjects, but no such asymmetries have been observed in left-handed subjects (Ozcan, Tulum, Pinar, & Baskurt 2004). This asymmetric motor skill can be explained not only by decreased use and training of the hand muscles, but also by the relatively decreased cortical excitability in the non-dominant motor cortex (Boggio, et al., 2006).

Disadvantage in motor and muscle coordination has also been found in the non-dominant hand. Sainburg and Kalakanis (2000) compared coordination patterns employed with left and right arms during rapid targeted reaching movements by right-handed persons. Results showed that hand trajectories and joint coordination patterns during movements were systematically different between the two hands. Inverse dynamic analysis also revealed substantial differences in coordination of muscles and inter-segmental torques for the left and right arms. These findings strongly suggest that distinct neural control mechanisms are employed for dominant and non-dominant arm movements. Related to this, Caeyenberghs et al. (2009) found that movements of the dominant body side were associated with additional activation of the brain as compared with non-dominant side.

More cognitive effort also appears to be required when performing tasks with the non-dominant hand. Mattay et al. (1998) examined activation patterns of the ipsilateral motor cortex area during simple and complex motor tasks for dominant and non-dominant hands (finger tapping tasks). The motor cortex includes regions of the cerebral cortex involved in the planning, control, and execution of voluntary motor functions. Mattay et al. showed that for most right-handed participants, fine motor movements of the left hand are less familiar, more complex and require more conscious effort, resulting in recruitment of additional motor cortex areas. The activation was similar to patterns seen during less familiar tasks performed with the right hand.
Recall task performance differences between dominant and non-dominant hands have also been experimentally investigated using the ROCF Test (Yamashita, 2010). Undergraduate participants (n=120; 60 men, 60 women) were randomly assigned to one of four groups based on the hand used in a copy trial and a recall test. Results showed that hand use had a minimal effect on performance in the copy trial. However, recall accuracy was lower when the non-dominant left hand was used in the copy trial than when the dominant right hand was used, regardless of the hand used in the recall test. This indicates that non-dominant hand use may influence cognitive functions in motor tasks.

In summary, the physical and cognitive characteristics of non-dominant hand performance by healthy subjects may be comparable to physical and cognitive limitations found in TBI patients. Table 7.1 summarizes research findings on non-dominant hand users, specifically observed physical and cognitive impairments. These correspond to limitations identified in other literature for TBI patients.

<table>
<thead>
<tr>
<th>Table 7.1. Findings of previous research on non-dominant hand performance.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TBI Patient Impairment</strong></td>
</tr>
<tr>
<td>1. Physical Impairment</td>
</tr>
<tr>
<td>- Motor Skill</td>
</tr>
<tr>
<td>- Motor Strength</td>
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<tr>
<td>- Motor Coordination</td>
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<tr>
<td>- Memory</td>
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</table>

Drawing correspondences among non-dominant hand performance and the behaviors of TBI patients is an important basis for making inferences on the effectiveness of VR-based training regimens for the pathological populations from test results on unimpaired subjects (under specific task conditions).
References


[DUMC Subteam]

In regard to the activities of the subteam in Durham, NC, the apparatus developed for the fMRI experimentation includes the following components:
(1) a MRI-compatible graphics tablet for copying and tracing geometric figures; and
(2) two mirrors, one of which will reflect geometric stimuli projected behind the subject
and the second will provide a top-down view of the hand.

The use of the mirrors is expected to minimize subject head motion in the fMRI tests.
Presentation of stimuli for copying or tracing will occur via a camera-lucida technique
following visual-angle calibration via input from the subject.