Project Participants

Senior Personnel

Name: Kaber, David

Worked for more than 160 Hours: Yes

Contribution to Project:

David Kaber is a professor of industrial and systems engineering (ISE) at North Carolina State University (NCSU). He has served as the principal investigator on the project. During the first project year, he 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. During the first project year, Kaber directed and supervised six graduates students working on the project.

During the second project year, Kaber coordinated the efforts of the project subteams at NCSU and Duke University, including: planning and execution of the first experiment on the effects of virtual reality (VR) and haptic interface design features on motor skill training; analysis of experiment data; identification of potential enhancements to the Augmented VR simulation for promoting training effectiveness relative to native forms of neuropsychological tests; and direction of literature reviews on augmented VR trainers for motor and visuo-spatial task performance. During the second project year, Kaber also directed and supervised six graduates students.

During the third project year, Kaber led the project team in planning, development and execution of the second experiment on the effects of augmented VR on motor skills training. Kaber directed the team in specification of features for the VR system, procedures for the experimental testing and therapy sessions, analysis of the experiment data and preparation of the technical report. Kaber also worked with several student subteams on generating a journal manuscript as well as conference proceedings for publication through the Applied Human Factors and Ergonomics Meeting as well as the Annual Meeting of the Human Factors Society. Kaber also gave a presentation summarizing the current state of the project research to the NCSU Rehabilitation Engineering Center. During the third project year, Kaber directed as many as five graduate students along with one post-doc.

Name: Lee, Yuan-Shin
Worked for more than 160 Hours:  Yes

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

During the second year of the project, Dr. Lee directed two additional research assistants in dividing time between the Computer-Aided Design Lab and Cognitive Ergonomics Lab. These persons included Xiaofeng Qin and Wenqi Ma. Dr. Lee provided the students with guidance on programming methods for enhancing the automated Rey-Osterreith Complex Figure (ROCF) scoring system and on statistical analysis of data collected during the Year 2 experiment. He also participated in regular technical meetings of the project and made input on decisions regarding project goals and tasks. He was also involved in presentations of the VR system and haptic device setups for visitors to the ISE Department.

During the third project year, Lee provided partial direction for one research assistant (Xiaofeng Qin). The student's work was focused on developing a new scoring system for the ROCF test. Lee and Kaber edited a manuscript prepared by Qin. Based on the direction of the project work, and Dr. Lee's personal research interests, he resigned his commitment to the project in fall 2011. Summer salary support for Dr. Lee was rebudgeted to support additional student effort.

Name: Tupler, Larry

Worked for more than 160 Hours:  Yes

Contribution to Project:
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 Duke 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. (Dr. Hayes remains willing to advise the project in the future upon completion of data collection.) Tupler also recruited three additional scientific collaborators during the first year: two with substantial expertise in fMRI and apparatus development (Dr. Jeff Browndyke 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 CTA portion of the study concerning motor-skill training undertaken by NCSU. Dr. Tupler also engaged in protocol development and procurement operations to consolidate the
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, which is the principal technology developed within the current effort. Finally, Tupler planned a fMRI experiment to assess the impact of VR-based motor skill training during the third year of the research project.

In the second year of the project, Dr. Tupler led the Duke team in two major activities, including: prototyping and refinement of the experimental apparatus for delivering complex drawing tests to subjects in a MRI scanner, and development of a refined automated ROCF measurement and scoring system for motor skill assessment. Dr. Tupler also worked with the NCSU subteam on: prototyping of the VR-based simulations of the block design (BD) task for the Year 2 experiment, VR software beta-testing, preparation of experiment protocols, experiment data analysis including expert scoring of ROCF drawings from test subjects, and results reporting. Beyond this, Dr. Tupler contributed to conceptual design of Augmented VR simulation enhancements for the Year 3 study and experiment planning to involve pathological subjects in fMRI scanning during neuropsychological test performance.

During the third project year, Dr. Tupler contributed to the NCSU team design of enhanced haptic and visual features for the VR-based BD training system. He also participated in usability tests of the new features and provided recommendations for the final system design used in the Year 3 experiment. Dr. Tupler was also closely involved in the planning of the experiment, direction of the data analysis and input on the Year 3 technical report. Dr. Tupler's primary work in this project year was directing Xiaofeng Qin on developing and analyzing and enhanced version of the automated ROCF scoring system. He also served on the dissertations committees of two of the student researchers working on the 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 Duke University Medical Center. During the first project year, she assisted the research 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 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. This data analysis is expected to occur in the third year of the project.

**Post-doc**  
**Name:** Gil, Guk-Ho  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**  
Dr. Guk-Ho Gil is a post-doctoral research engineer and has served as a project director for the Cognitive Ergonomics Lab subteam since January 2011. Before this time, he was a PhD student in ISE and worked as a half-time research assistant. As a project director, he was responsible for leading the research team to successful completion of the second and third year.
experiments. He coordinated and facilitated regular technical meetings. He designed and maintains the website for the NCSU/NSF-Haptics Project, which is used for communicating project status updates and materials among team members (http://www.ise.ncsu.edu/ergolab/research/NSF_Haptic).

During summer 2011, he led a usability test to improve the features of the VR system developed as part of this research. He also led the research team in preparing and submitting a manuscript to the journal of Assistive Technology. Furthermore, he worked with two student subteams in making paper submissions to the Applied Human Factors and Ergonomics conference based on the Year 2 study. Finally, he led the research team in preparation of both the second and third year technical reports.

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 first year of the grant, 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 conducted a separate literature review on cognitive and physical implications of mTBI. Finally, he defined the conditions and laid-out the procedures for the first VR-based motor skill rehabilitation study executed in the fall of 2010.

During the second project year (2010), Michael served as co-director for the Cognitive Ergonomics Lab subteam through a half-time research assistantship. During this time he was primarily responsible for coordinating the writing efforts of the study plans, experimenter instructions, and final report for the Year 1 study. He also contributed to the design of the VR software used in the experiment. He was responsible for testing the VR software throughout the development life cycle and led the software beta test. During the Year 2 experiment, he was responsible for coordinating the experiment schedule. He also participated in the writing of the Year 2 technical report.

Michael continued his half-time research assistantship during the third project year (2011). He contributed to the usability testing of the VR system software and hardware during the summer term. As in Year 2, Michael prepared study plans for the Year 3 experiment as well as subject instructions. During execution of the experiment, he was responsible for recruiting and coordinating the participant schedules. He also helped prepare a manuscript summarizing the Year 2 results for Assistive Technology. He will present parts of the Year 2 and 3 studies at the Applied Human Factors and Ergonomics and Human Factors and Ergonomics conferences this summer and fall, respectively. Most recently, Michael worked on summarizing the Year 3 experiment for the current technical report. Michael also recently completed his third year as a PhD student and is planning to defend his dissertation proposal this fall.
Name: Li, Yingjie

Worked for more than 160 Hours: Yes

Contribution to Project:
Yingjie Li was a full-time PhD student in ISE. During the first year of the project, 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 graduated in August of the same year. She was directed in her research by David Kaber and Yuan-Shin Lee. Larry Tupler also served as one of her dissertation committee members.

Upon completion of her PhD, Yingjie took a programmer position at a computer-aided design software

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 the first 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 was on the interoperability of haptic devices with 3-D VR displays.

During the second project year, Linus worked as a half-time research assistant to David Kaber. Linus was the lead developer responsible for implementing the software platforms for delivering the VR-based task simulation. The VR-based task simulation included Basic and Augmented versions of the BD subtest from the Wechsler Abbreviated Scale of Intelligence (WAIS). Working with Xiaofeng Qin, Linus also ported an existing electronic version of the ROCF test to a new platform for experimentation purposes. He conducted a literature review on augmented VR trainers for motor and visuo-spatial tasks as a basis for enhancing the BD task software and improving subject training performance in the Year 2 experiment.
During the third project year, Linus continued his work as a half-time research assistant to David Kaber. Linus was responsible for implementing haptic and visual features in the VR-based BD task simulation. He also developed a training application for haptic device familiarization for subjects. He served as the lead on a usability test and analysis of the new VR system features. As part of the Year 3 experiment, Linus conducted data collection and initial data analysis. He was partly responsible for the VR therapy sessions. Linus is planning to defend his dissertation proposal by the close of summer 2012.

**Name:** Swangnetr, Manida  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**  
Manida Swangnetr was a PhD student in ISE. She worked as a half-time research assistant to Yuan-Shin Lee and David Kaber during the first and second years of the project. Her focus was on identifying functional limitations associated with mTBI and drawing correspondences with functional limitations in non-dominant hand use. She was also involved in developing storyboards and prototypes of block matching tasks as a basis for the initial VR motor skill training simulation. Beyond this, she wrote the instruction set for administration of the Matrix Reasoning subtest of the WAIS for delivery during the Year 2 experiment.

Manida defended her dissertation in September of 2010 and she graduated in December of the same year. Her dissertation committee members included Drs. David Kaber and Yuan-Shin Lee. Upon completion of her research and graduation, Manida took a faculty position at Khon Kaen University in Thailand in the area of Production Technology.

**Name:** Zhang, Yu (Zeno)  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**  
Yu (Zeno) Zhang was a full-time Phd student in ISE. During this first year of the project, she worked as a quarter-time research assistant to David Kaber. 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 experimental study on VR-based motor skill training.

During the second year of the project, Zeno also worked as a quarter-time research assistant to David Kaber. She and Wenqi Ma were responsible for designing the physical workstation layouts used to present the VR displays to users in the first experimental study and to prepare the experimenter instructions for the test scenarios. She also worked on conceptual designs and storyboards for VR implementation of the block matching and positioning task with Manida Swangnetr, a prototype contributing to the final VR simulation design. During the Year 2 experiment, Zeno conducted the pre- and post-test sessions (i.e., ROCF tests with haptic device and native forms of the MR and BD tests). She also conducted statistical data analyses for ROCF pre- and post-test sessions. Her results contributed to the Year 2 technical report.
During the third year of the project, Zeno worked as a half-time research assistant to David Kaber. As part of the Year 3 experiment, she conducted statistical analyses on the pre- and post-test session data (i.e., ROCF test with haptic device and native forms of the MR and BD tests).

Yu Zhang completed her doctoral dissertation research in October 2011 and graduated in December of the same year. She was directed in the research by David Kaber. Christopher Mayhorn, David Dickey, Russell King and Joseph Hummer served as her dissertation committee members. After Zeno defended her Ph.D. dissertation, she took a Human-Machine Interface researcher position at GM in Warren, MI.

Name: Zhu, Biwen

Worked for more than 160 Hours: Yes

Contribution to Project:
Biwen Zhu was a full-time PhD student in ISE. During the first year of the project, he worked as a quarter-time research assistant to David Kaber. Biwen worked on material specification and assembly of prototype physical workstations for presenting VR displays and haptic devices to users. He also setup a workstation integrating a Novint Falcon device. He 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.

During the second year of the project, Biwen worked as a quarter-time research assistant to David Kaber. He was responsible for writing the instruction manual for the BD task training as part of the Year 2 experiment. During the experiment, he conducted the motor therapy sessions. He also conducted the statistical data analyses for the therapy sessions, which were used as part of the results for the Year 2 technical report. He also contributed to the literature review, methodology and discussion sections of the report.

During the third year of the project, Biwen worked as a half-time research assistant to David Kaber. As part of the Year 3 experiment, Biwen moderated the therapy training sessions. Biwen was also responsible for conducting statistical analyses on the BD scores collected during the therapy sessions. Biwen worked with Linus Jeon on a conference paper entitled 'Usability Evaluation of a Virtual Reality System for Motor Skill Training', which is to be published in the proceedings of the 2012 Applied Human Factors and Ergonomics Conference.

Biwen completed his doctoral dissertation research in October 2011 and graduated in December of the same year. He was directed in his research by David Kaber and Yuan-Shin Lee and Larry Tupler also served on his dissertation committee. Upon completion of his Ph.D., Biwen took a usability specialist position at Monsanto in St Louis, MO.

Name: Qin, Xiaofeng

Worked for more than 160 Hours: Yes

Contribution to Project:
Xiaofeng (Caesar) Qin is a full-time Masters student in ISE. He worked as a full time research assistant to Yuan-Shin Lee. He was responsible
for setting-up the ROCF hardware and software test platforms for the experiment. He also worked on revising and enhancing the ROCF drawing and scoring systems that were originally developed by Li et al. (2010). During the experiment, he conducted motor control therapy sessions along with Biwen Zhu. He also performed the ROCF scoring for the experiment and statistical analysis of the ROCF data. His main focus has been on revising and further developing the ROCF software platform.

During the third project year, Caesar was also responsible for integration of the ROCF-based testing in the second experiment. He administered pre- and post-therapy tests with subjects to assess complex motor skills. His main work on the project during this period was developing an enhanced version of the automated ROCF scoring system. Caesar tested and validated the new system and prepared a manuscript on the study for submission to a journal. Drs. Tupler and Kaber directed Caesar in this effort.

In the spring of 2012, Caesar completed his work on the project and was assigned to another NSF grant under Dr. Lee's supervision.

Name: Ma, Wenqi
Worked for more than 160 Hours: Yes
Contribution to Project:
Wenqi (Janet) Ma is a PhD student in ISE. She joined the research group in the second year of project as a half-time research assistant to Yuan-shin Lee. Janet and Yu Zhang were responsible for designing the physical workstation layouts used to present the VR displays to users in the first experimental study and to prepare the experimenter instructions for the test scenarios. Also, they both took charge of administering the pre- and post-test sessions (i.e., ROCF tests with the haptic device and native forms of the MR and BD tests). Janet also conducted statistical analyses on the ROCF drawing and confidence rating data.

During the third year of the project, Janet worked as a half-time research assistant to David Kaber. She conducted pilot tests for the VR therapy sessions in which new haptic and visual simulation features were presented to subjects. These features were designed for the second experimental study. During the experiment, Janet administered the pre- and post-test sessions (i.e., ROCF tests with the haptic device and native forms of the EFT and BD tests). In addition, Janet was responsible for the statistical analyses of test and training data collected during the second experimental study. Her work contributed to the methodology, results, and discussion sections of the Year 3 report. Janet plans to defend her dissertation proposal by the close of summer 2012.

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 Duke University Medical Center. 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 Alzheimers Disease Research Center at DUMC. He is affiliated with the Brain Imaging and Analysis Center (BIAC) at Duke.

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.

During the second year of the project, Dr. Voyvodik collaborated with Dr. Tupler to write software code for presentation of visual stimuli in the MRI scanner and for recording patient behavioral and physiological responses in using the fMRI apparatus in complex figure drawing trials. It is expected that this software will be used in Year 4 of the project to facilitate the third experimental study involving a pathological subject population.

Durham VA Medical Center
Ms. Nan Verbel is an occupational therapist at the Durham VAMC. During the first project year, she advised the research team on the principles of occupational therapy for the benefit of the CTA specification of rehabilitative techniques for sensorimotor rehabilitation of TBI.

Duke University Surgical Instrument Shop
Duane Copeland is a staff member in the Duke Surgical Instrument Shop. During the first project year, Dr. Tupler worked with Duane to design a novel apparatus for holding a non-ferromagnetic graphics tablet in a MRI scanner for patient drawing and tracing tasks during fMRI trials.

Other Collaborators or Contacts
None to identify at this time.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
(Please see attached file for activities of the research team during the third project year.)

Findings: (See PDF version submitted by PI at the end of the report)
(Please see attached file for the findings of the research team during the third project year.)

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

(1) post-doc (Gil) training on research project management practices, including organization of team meetings, agenda preparation, task assignments, progress tracking and follow-up, along with participation in project report writing;
(2) graduate student (Clamann, Jeon, Ma, Qin, Zhang, Zhu) training on usability analysis and testing of VR system design features;
(3) graduate student (Jeon) learning on existing augmented VR training systems and visual and haptic design features through technical literature review;
(4) graduate student and post-doc (Clamann, Gil and Jeon) training on prototyping of VR system design features for motor skill training;
(5) graduate student and post-doc training (Gil and Jeon) on programming VR simulations and haptic device interfaces for motor skill training applications;
(6) graduate student and faculty training (Qin, Tupler) in computerizing standardized neuropsychological tests (e.g., the ROCF test) and developing automated scoring systems using C++ applications;
(7) graduate student (Clamann, Jeon, Ma, Zhang and Zhu) training in human factors experiment design, participant recruiting and testing, data collection and analysis and report development;
(8) graduate student training in delivery of computerized neuropsychological tests for baseline motor skill characterization, including the Group Embedded Figures Test (Ma), the ROCF test (Qin) and the BD task (Jeon, Zhu);
(9) graduate student training in delivery of motor skill therapy sessions (Jeon, Zhu) using native forms of psychomotor tests and VR systems; and
(10) graduate student training (Clamann, Ma, Qin, Zhu) in advanced statistical analysis methods for application to human factors experiment data.

Related to these training opportunities, Yu Zhang prepared and successfully defended her dissertation on the effects of visual and cognitive behavior on psychomotor task performance in dynamic environments and a machine learning approach for classification of operator states. Biwen Zhu also prepared and successfully defended his dissertation on the effects of types and modalities of feedback in motor control skill training. Linus Jeon drafted his proposal topic on development of an adaptive VR-based block design task with a haptic control interface and physics engine for motor skill training.

Publications generated by the NCSU and Duke teams within the past year have included: the Year 2 technical report, a journal manuscript to Assistive Technologies, two conference proceedings papers based on the Year 2 experiment, and a conference proceeding paper based on the Year 3 experiment. These publications may serve as guides for other researchers on the design and prototyping of VR simulations and haptic interfaces for motor control training applications. Additional journal manuscripts are to be prepared based on the Year 3 experiment and refinements to the VR-based ROCF test and scoring system.

Some of the above publications present results on the impact of resistive and assistive haptic feedback on performance (speed and accuracy) in a VR simulation of the BD task as well as the effect of visual and spatial information processing aids in guiding user in
block orientation and placement for virtual pattern generation. They also provide additional insight into how visual and haptic assistance may affect strategy development for operators with different perceptual styles (e.g., field dependent/independent). The results may be useful to other researchers in terms of identifying what types of haptic and visual aids as part of an augmented VR system may actually serve to accelerate user learning of motor behaviors and best support task performance. The research also provides some guidance for VR application developers in terms of how to implement aids for different types of users.

The identified writings may also serve as a basis for the design of experiments for assessing the effectiveness of VR design for motor skill training. The pre- and post-test methodology used in the Year 3 experiment, as well as definition of the motor training or therapy regimen, were based on extensive pilot testing and the results of the Year 2 experiment. This type of information is very useful for structuring experiments to make accurate assessment of training conditions by controlling for individual differences in ability and stamina. The results of the Year 2 and Year 3 experiments and manuscripts also identify specific psychomotor tasks that are sensitive to motor skill training, such as the ROCF copy test, as well as those that are not, such as the Matrix Reasoning test. This information may also be useful to other researchers using pre- and post-therapy testing methodologies for assessing motor training system designs.

**Outreach Activities:**

The NCSU subteam held several tours of the ISE Ergonomics Lab for visitors during the course of the third project year. Visitors included students in the Armed Forces, ergonomics professionals attending training courses at the Ergonomics Center of North Carolina, K-12 students attending engineering education summer camps through the ISE department, mentors and professionals from IBM's Pathfinder program, guests attending the Engineering Open House, visiting professor Dr. Nancy Currie, NCSU Textile faculty, as well as visiting faculty from Chulalongkorn University in Thailand. As part of the tours, visitors were shown the current VR workstation setups for the NSF haptics project. They were also provided with demonstrations of the VR simulations and were permitted to experience the haptic control interface conditions.

Dr. Kaber presented the results of the ongoing research as part of seminars for the NC State College of Engineering, Rehabilitation Engineering Research Center, and the Human Factors and Ergonomics Brown Bag Seminar Series hosted by the NC State Department of Psychology.

The Duke subteam has nothing to report on outreach activities at this time.

**Journal Publications**


Clamann, M., Li, Y. & Kaber, D. B., "Validation of a Haptic-Based Rey-Osterrieth Complex Figure Testing System", IEEE Transactions on Information Technology in Biomedicine, p., vol., (2012). in preparation,


Books or Other One-time Publications


Clamann, M., Gil, G-H, Kaber, D. B., Zhu, B., Swangnetr, M.,
Web/Internet Site

URL(s):
http://www.ise.ncsu.edu/ergolab/research/NSF_Haptic/

Description:
This website is an information repository and dissemination portal for the NCSU/NSF Haptics Project. The site provides documentation on the the Year 1, 2 and 3 research activities. The cognitive task analysis results from Year 1 are available along with paper and electronic prototypes of VR simulations for motor skill training. Images of the custom VR workstation designs used in the pilot study and Year 2 experiment are available. The site also presents videos of various versions of the existing VR block design (BD) simulation. Beyond this, there are links to all documents used for conducting the Year 2 and 3 experiments. The site also includes links to all publications and presentations resulting from the research in draft or final forms. Finally, the site documents the agendas and action items for all team meetings as part of the project effort.

Other Specific Products

Product Type:
Software (or netware)

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

Sharing Information:
The NCSU 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 was used in the second 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 during the third project year.)

Product Type:
Software (or netware)

Product Description:
Virtual Reality Simulation of the WAIS Block Design Test?

Sharing Information:
The NCSU subteam developed a Visual C++ software application simulating one of the tests as part of the Wechsler Abbreviated Scale for Intelligence (WAIS) III system. The WAIS is used to measure intelligence for unimpaired adults. The Block Design test is composed of 14 patterns and evaluates visuospatial and motor skills by requiring subjects to build replicas using identical blocks printed with simple patterns. The software application we developed includes basic and augmented VR versions of the BD test. The augmented version can aid users in reducing learning time with a haptic control device. The current augmented features include force feedback in block positioning and orientation as well as visual guides for orienting blocks and pattern previews for accurate positioning. The VR interface is presented on a PC using the NVIDIA 3D vision kit, which includes 3D goggles and an emitter. The haptic control interface incorporates a Phantom Omni haptic device.

The VR simulations will eventually be made freely available to the public through the research project website (http://www.ise.ncsu.edu/ergolab/research/NSF_Haptic/).

Product Type:
Software (or netware)

Product Description:
Enhanced ROCF Scoring System for Motor-Skill Assessment?

Sharing Information:
The Duke team developed a new software application (using Delphi (Object Pascal) code) to score the Rey-Osterrieth Complex Figure (ROCF) directly from bitmap files generated by a PHANToM haptic device. The motivation for this program development was that scanning of the original ROCF figure revealed a slight flaw including a negative slope in the horizontal axis from left to right equaling 2 pixels. The correction for this flaw through the automated scoring system allows for exact measurements of each ROCF unit at the level of the individual pixel. Other software-coding strategies are under development for scoring the bitmap-file output, pixel by pixel, for each subject’s ROCF copy. There are two scoring methodologies including a user-guided system in which the operator indicates to the computer the unit to be scored along with identification of the ROCF unit, and a fully automated system that segments all lines, circles, and dots within the drawing. The automated scoring program is expected to accept user data files with spatial and temporal information on drawing performance and regenerate the ROCF drawings in real time for unit scoring.

Duke plans to conduct a review of prior software applications for this purpose to confirm the novelty of the approach. The University will likely pursue an invention disclosure after applying the software in the Year 3 experiment.

Product Type:
Instruments or equipment developed

Product Description:
fMRI Fixture for Graphics Tablet Mounting and Suspension During Scanning

Sharing Information:
The Duke subteam designed an fMRI apparatus for measuring constructional praxis in an fMRI machine. This is a novel, semicircular platform supporting an adjustable, non-ferromagnetic graphics tablet for input of copy and tracing fMRI conditions. They have also written software code for presentation of visual stimuli through the tablet and recording behavioral and physiological responses of users. Duke plans to pursue invention disclosure after the apparatus is used for completion of the study fMRI protocol to ensure robustness and to determine whether additional design enhancements are required. The apparatus is generally useful for fMRI tests in which a graphics tablet could be used for fine motor-skill applications.
Software (or netware)

**Product Description:**
Virtual reality dice manipulation training module

**Sharing Information:**
The NCSU subteam developed a Visual C++ software application designed to orient users to the controls and visual interface used in the Virtual Reality Block Design task, also developed as part of this research. The interface requires users to quickly orient and move a virtual six-sided die from one side of the screen to a target on the other. The movements required are similar to those used during the experiment.

The VR simulations will eventually be made freely available to the public through the research project website (http://www.ise.ncsu.edu/ergolab/research/NSF_Haptic/).

**Contributions**

**Contributions within Discipline:**
The activities of the NCSU subteam have served to advance industrial engineering, specifically in the area of human factors. There is a paucity of research on approaches to user-centered design of VR-based simulations for motor control skill development. We developed an approach to simulation of standardized psychomotor tests for motor ability assessment and integration of haptic control devices.

The objective of our work in the first project year was to create platforms for empirical study of the effectiveness of VR-based motor control therapy regimens. In preparation for the Year 2 experiment, we created visual and haptic aids as part of the VR simulations with the expectation of accelerating motor task learning rates and further supporting user performance. Beyond this, the research team conducted a novel experiment to quantify the psychomotor performance effects of different therapy regimens involving basic and augmented VR simulations. The results of the Year 2 experiment were documented in a journal manuscript submitted to Assistive Technology along with a conference proceeding paper to be published through the Applied Human Factors & Ergonomics Conference.

In the current project year, we enhanced a number of visual and haptic features as part of the VR simulation for motor skill training. We conducted usability test on the new features along with a designed experiment to test the effectiveness of the visual and haptic aiding for promoting user performance and training. The results of the usability study (reported in the Findings section) are to be published as a conference proceeding paper through the Applied Human Factors & Ergonomics Conference. The results of the Year 3 experiment will be disseminated through a journal publication, as with the results of the Year 2 study.

In general, the findings of this research provide evidence of how human factors design methods can be used to enhance VR-based simulations for motor skill training. Such simulations may also be useful for training skills required as part of industrial assembly tasks by healthy working populations, in addition to the application for impaired users attempting to recover skills impacted by mTBI.
Contributions to Other Disciplines:
All of the research findings of the NCSU and Duke subteams are expected to contribute to the disciplines of neuropsychology and rehabilitation. The NCSU subteam activities during the first project year were aimed at creating platforms for computerizing standardized neuropsychological tests. The importance of this work is that such systems may be used for automated assessment of impaired user capabilities and support clinical diagnoses. Such tests have previously been administered manually and scoring of user capabilities has occurred by clinician subjective judgment.

The research as part of the second project year included review of literature on augmented VR for motor skill training. On the basis of the review and observations during the Year 2 experiment, we formulated design recommendations for haptic aids in VR simulations as well as visuo-spatial information processing cues to facilitate high performance of users in psychomotor tasks.

In Year 3, the haptic and visual aid designs were prototyped as part of the VR simulation. All features were expected to have value for researchers working in neuropsychology and rehabilitation with interests in developing advanced assistive technologies to accelerate patient motor learning rates. Usability tests identified those features that expert VR users considered to have the greatest potential for promoting motor skill performance and training. We tested a select set of the features in an experiment and found that haptic aiding benefited visuospatial task training and that the visual aids benefited psychomotor task training. In addition, the methodology we employed in the research experiments provides an example for others to follow in studies of advanced motor therapy technologies with healthy and impaired populations, specifically persons having experienced mTBI.

With respect to the research at Duke, the apparatus developed for psychomotor task performance during fMRI as part of the Year 2 project effort 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. In addition, the new enhanced automated ROCF (Rey-Osterrieth Complex Figure) measurement and scoring system developed through the Year 2 and 3 research activities is expected to be more accurate and reliable in evaluating patient performance in figure reproduction as compared to clinician manual scoring, according to the existing guide for the neuropsychological test. A prototype system was developed in Year 2 and testing and validation occurred in Year 3. A manuscript has been prepared based on this research and is to be submitted to the Journal of Neuropsychology for consideration for publication. Duke is also extending research on the new scoring system to ensure compatibility with a range of high-fidelity haptic devices in VR simulations of the ROCF test, including the Sensable Technologies Omni and Phantom, in terms of the types and formats of data output by devices.

Contributions to Human Resource Development:
This project is providing specialized training for NCSU graduate students in engineering design through the development of VR
simulations and haptic control interfaces to support motor skill training for persons having suffered forms of mTBI. The students on the project team have also learned how to rapidly prototype new VR visual and haptic design features for test purposes. In each year of the project, student subteams have been involved in programming the VR platforms for delivery of task simulations as well as presenting haptic and visual aids for facilitating user performance. The students have also honed their skills in software usability evaluation as well as human factors experimentation. The Year 2 study was a first experience for many of the team members in delivering an experiment structured based on a simplified occupational therapy regimen. In Year 3, the students conducted a usability evaluation with expert users by applying a questionnaire focused on specific system features. The Year 3 experiment also allowed the students to further practice their skills at delivering a pseudo-therapy regimen to healthy participants. Beyond this, the students have learned how to work with various subject populations in delivering complex psychomotor tests and conducting motor control therapy sessions.

Finally, the second and third year activities also provided opportunities for the students to conduct technical literature reviews and to apply their knowledge of inferential statistics (parametric and non-parametric) to experimental data. These activities have also led to preparation of journal manuscripts and conference proceedings papers.

In general, it is expected that this training will improve student performance as research assistants at NCSU. The NSF project work is also expected to support student 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 the second project year, the grant and ISE Department funds were used to acquire additional stereoscopic display technologies and haptic control devices for the Cognitive Ergonomics Lab. Specifically, the lab purchased a Samsung 3D HDTV compatible with existing nVidia stereo viewing goggles. The TV was integrated with the lab VR workstations for presentation of a larger format of the BD task simulation. We can now present a full-scale (life-like) simulation of the task to users with the 3D TV. In addition to the display technology, the lab acquired multiple Sensable Omni haptic devices.

In Year 3 of the project, there were three fully functional haptic VR workstations available for student use in the Cognitive Ergonomics Lab. This equipment was used for prototyping the enhanced VR simulation with haptic and visual aids. The systems were also used for conducting the usability evaluation with expert users. Finally, the workstations were used for designing, planning and executing the Year 3 experiment. Having multiple VR systems with comparable configurations is critical to the project success, as some systems can be used for development work at the same time others are used for experiment purposes.

Beyond the use of the above identified resources for project activities, the VR workstations are also used in student dissertation
research, directly related to the grant. This will include Michael Clamann’s study of haptic aiding systems for training writing skills in VR and Linus Jeon’s research on developing adaptive VR systems for supporting effective haptic control in simulations of basic psychomotor tasks.

**Contributions Beyond Science and Engineering:**

The virtual BD (block design) task was developed as part of the Year 2 research. The simulation was tested in a preliminary motor training experiment during Year 2 and proved to be highly effective for causing motor skill learning in healthy persons performing complicated motor tasks with their non-dominant hand. In general, there were dramatic increases in task performance time and accuracy over the three-day experimental period. With the native form of the BD task, average time to completion decreased by as much as 150 ms. However, under the VR conditions, task time reductions were, on average, 450 ms for the basic VR simulation and 375 ms for the augmented VR simulation. These results support the general effectiveness of the BD task for basic motor skill development, which was found to be relevant to complex drawing reproduction and assembly task in post-training tests.

More importantly, the VR versions of the BD task investigated in Year 2 showed learning rates, which were significantly greater than for the native form of the task. This suggests that the VR simulation may have some advantage over the native task in terms of accelerating motor skill development.

In Year 3, the VR BD task simulation was enhanced with several visual and haptic aids to promote user performance. Highlighting of blocks for placement in a target grid as part of design reconstruction proved to be helpful for promoting users performance during therapy sessions but had the surprising effect of improvement in post-training psychomotor test performance. The haptic aids included block snap and rejection forces as well as automatic alignment forces for block placement in a target grid space. These features also served to promote user performance during therapy sessions but had the surprising effect of improvement in post-training visuo-spatial test performance. It was clear from the results of the Year 3 study that requiring users to rely more on their own abilities for BD task performance led to greater training or learning of skills related to those abilities.

In general, the VR simulations developed as part of this research provide for automated psychomotor task performance data collection and analysis. These simulations might support therapists or clinicians, who could use them for diagnostic purposes. For these reasons, we believe the enhanced VR simulation of the WAIS BD task with haptic control interface has substantial commercial potential. At a fundamental level, the software presents the BD task with high fidelity and supports VR system user assembly of designs with various haptic control devices. On a more advanced level, the system presents visual and haptic aids that have been customized based on user behaviors in the task and that facilitate highly realistic performance.

The VR BD software 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 virtual BD simulation an ‘open source’ project accessible to all users through the Internet in order to accelerate enhancements and extensions of the simulation for motor skill testing and training.

Beyond the VR BD software, two other software applications have been created by the research team, which have commercial potential. These include the computerized ROCF task and scoring system as well as the new VR-based dice motor skill training program. The former application has been developed over several years of the project and currently presents a usable and stable interface for ROCF reproduction. As a result of recent Duke project activities, the application includes a more robust scoring system with: a graphical user interface for replay of test subject figure reproduction; precise algorithms for drawing feature recognition and assessment; a utility for describing dynamic motor behaviors of test subjects during figure reproduction; and a utility for determining how dynamic motor behavior analysis contributes to test subject ability assessment beyond static drawing analysis. With respect to the dice motor skill training application, the software provides a platform for users to learn how a haptic device can be used to move and rotate block objects in a virtual space. It also supports learning of visuo-spatial skills by requiring die position and orientation matching to a target. The ability of users to improve in haptic device control and achieve asymptotic performance in the simulation has been experimentally verified.

All of the VR-based prototypes of existing psychomotor tasks, and any enhancements 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 Conference
Appendix A:

Appendix A.1. Block design flowchart for haptic condition

Look at the pattern to gain spatial organization info.

Find matching choices among scattered blocks

Does a match exist?

Yes

Adjust the block to matching one element

No

Reexamine the model area to see where to place the block

Place the block in the destination

Is the placement correct

Hearing Ding! Snap to the destination

Have all blocks been placed?

Yes

Confirm the completion

No

Reject from the area to be placed

Remove the incorrect block
Appendix A.2. Block design flowchart for visual condition

1. Look at the pattern to gain spatial organization info.
2. Find matching choices among scattered blocks.
3. Does a match exist?
   - Yes: Reexamine the model area to see where to place the block.
   - No: Adjust the block to matching one element.
4. Place the block in the destination.
5. Is the placement correct?
   - Yes: Flashing and triggered.
   - No: Highlight matching triggered Hearing Drag.
6. Have all blocks been placed?
   - Yes: Confirm the completion.
   - No: Remove the incorrect block.
Appendix A.3. Block design flowchart for combination condition

1. Look at the pattern to gain spatial organization info.
2. Find matching choices among scattered blocks.
3. Does a match exist?
   - No: Adjust the block to matching one element.
   - Yes: Proceed to the next step.
4. Examine the model area to see where to place the block.
5. Place the block in the destination.
6. Is the placement correct?
   - Yes: Highlight matching triggered. Hearing Ding. Snap to the destination.
7. Have all blocks been placed?
   - Yes: Confirm the completion.
   - No: Go back to looking at the pattern.
Appendix B: Usability Test Form

**VR Trainer Features Questionnaire**

For the following statements, please indicate how strongly you agree or disagree using this scale:

<table>
<thead>
<tr>
<th></th>
<th>1 Strongly Disagree</th>
<th>2 Disagree</th>
<th>3 Slightly Disagree</th>
<th>4 undecided</th>
<th>5 Slightly Agree</th>
<th>6 Agree</th>
<th>7 Strongly Agree</th>
</tr>
</thead>
</table>

**Block Translucency**

1. Translucency helped me recognize the patterns on a block.
   - 1 2 3 4 5 6 7

2. Translucency would be helpful as part of the VR training system.
   - 1 2 3 4 5 6 7

**Auditory Feedback**

3. Auditory cues promoted immersion in the VR reality.
   - 1 2 3 4 5 6 7

4. Auditory cues would promote user performance.
   - 1 2 3 4 5 6 7

5. Was there any inappropriate or distracting sound in the test simulation?
Control Gain

6. For the gain ratio of 1:2, block manipulation occurred as intended.
   1  2  3  4  5  6  7

7. For the gain ratio of 1:3, block manipulation occurred as intended.
   1  2  3  4  5  6  7

8. The increased gain ratio was helpful in terms of task completion time.
   1  2  3  4  5  6  7

9. The increased gain ratio was helpful in terms of convenience of hand grip.
   1  2  3  4  5  6  7

10. The increased gain ratio would reduce usability issues, such as twisting of the wrist or repeated pick-n-place of virtual objects.
   1  2  3  4  5  6  7

Flashing Grid

11. The grid was visually distracting.
   1  2  3  4  5  6  7

12. The grid feature would help Field-Dependent users recognize block faces in design patterns.
   1  2  3  4  5  6  7

Rolling Blocks

13. It took a long time to learn how to roll a virtual block with the haptic device stylus.
   1  2  3  4  5  6  7
14. It was difficult for me to rotate a block by 'rolling'.

1 2 3 4 5 6 7

15. I had difficulty rolling a block by pushing and releasing the button on the stylus.

1 2 3 4 5 6 7

16. It would be helpful if the block rolling capability was combined with the increased control gain.

1 2 3 4 5 6 7

**Grasping Blocks**

17. It took a long time to learn how to manipulate a virtual block with the haptic device stylus.

1 2 3 4 5 6 7

18. It was difficult for me to pick-up a block by pushing and releasing the button on the stylus.

1 2 3 4 5 6 7

19. It was easier for me to pick-up a block by 'touching a block'.

1 2 3 4 5 6 7

20. It would be helpful if the block grasping capability was combined with the increased control gain.

1 2 3 4 5 6 7

21. Any comments?

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________
Appendix C: GEFT description

Test 2: Embedded Figure Test

Introduction
The task for each trial is to locate a previously seen simple figure within a complex figure, which has been organized to obscure or embed the sought-after simple figure.

Materials
The following materials are required for each subject:
1. Stop-watch,
2. Test booklets, and
3. Black pencils with erasers.

Procedures
The experimenter sits across from the participant to give instructions and observe the participant. Each participant will receive a booklet containing the EFT Test and will enter responses on the cover page of the booklet. Each participant will be required to perform all tasks in the booklet. Each tracing task has a 2-minute limit.

Scoring
1. The score is the total number of simple forms correctly traced in the second and third sections.
2. Omitted items are scored as incorrect.
3. All lines of the simple form must be traced (including the interlines), and no extra lines can be added by the subject.

Embedded Figure Test Script

<table>
<thead>
<tr>
<th>Start (Reading Directions)</th>
<th>Distribute test booklets and pencils:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Now start reading the Directions, which include two practice problems for you to do. When you get to the end of the Directions on Page 3, Please stop. Do not go beyond Page 3.</em></td>
</tr>
</tbody>
</table>
More directions | When a subject has finished reading the directions on Page 3...
---|---
| *Before I give the signal to start, let me review the points to keep in mind:*
| *• Look back at the simple forms as often as necessary.*
| *• ERASE ALL MISTAKES.*
| *• Do the problems in order. Don’t skip a problem unless you are absolutely “stuck” on it.*
| *• Trace ONLY ONE SIMPLE FORM IN EACH PROBLEM. You may see more than one, but just trace one of them.*
| *• The simple form is always present in the complex figure in the SAME SIZE, the SAME PROPORTIONS, and FACING IN THE SAME DIRECTION as it appears on the back cover of your booklet.*

| First Section | This section is primarily for practice with the format of the test. Proctors should give additional explanations to subjects who seem to be having difficulty with the set of practice items.
---|---
| *When I give the signal, turn the page and start the First Section. You will have 2 minutes for the 7 problems in the First Section. Stop when you reach the end of this section.*
| *Go ahead!*  
Scorers should, however, scan this section before starting as a means of making sure the subject has understood the test directions.

| Stop 1st Section & Start 2nd Section | After 2 minutes:  
*STOP – Whether you have finished or not.*

| *When I give the signal, turn the page and start the Second Section. You will have 5 minutes for the 9 problems in the Second Section. You may not finish all of them, but work as quickly and accurately as you can.*

| Stop 2nd Section & Start 3rd Section | After 5 minutes:  
*STOP – Whether you have finished or not.*

| *When I give the signal, turn the page and start the Third Section. You will have 5 minutes for the 9 problems in the Third Section.*

| Stop 3rd Section | After 5 minutes:  
*STOP – Whether you have finished or not.*

| *Please close your test booklets.*
NCSU AND DUKE FINDINGS

1. Objective

In the second year of this project, the research team successfully completed a study assessing the effects of psychomotor training with a virtual reality (VR) system integrating a haptic control interface. The experiment design replicated a simplified occupational therapy regimen. The Rey-Osterrieth Complex Figure (ROCF; Osterrieth, 1944; Rey, 1941) test represented the occupational task, and training was provided using a VR-based simulation of the block design (BD) subtask from the Wechsler Abbreviated Scale of Intelligence (WASI: The Psychological Corporation, 1999). Three different forms of training were provided, including the native BD task, basic VR without haptic aiding, and augmented VR featuring visual and haptic enhancements. The results of the Year 2 study showed benefits as a result of psychomotor skill training with the augmented features, in particular with respect to training in skills related to the ROCF. However, the augmented condition included a combination of haptic and visual assistance, and a question remained regarding the extent to which those two forms of assistance contributed individually to psychomotor training. The project team, therefore, developed two new experiment conditions using the VR simulator, one featuring haptic assistance and one with visual assistance, for testing in the third of the project.

In addition to the proposal to separate the haptic and visual aiding to identify individual contributions to psychomotor training, there was an interest in improving the usability of the existing VR system feature set. Observations made by experimenters during data collection as part of the Year 2 study suggested the software could benefit from usability improvements in terms of haptic and visual aiding.

With these observations in mind, in Year 3 the project team began a detailed review of the visual and haptic aspects of the simulation design to inform modifications to be implemented in a second experimental study. This work resulted in a design proposal for separating the visual and haptic aiding features. Additional modifications were subsequently proposed based on observations made by the project team. Prototypes were developed based on the proposal and a usability study was conducted to identify combinations of features that would be used during data collection in Year 3. The following sections describe evolution of the features through the proposal, a literature review, and the usability test. This information is followed by description of the experimental study investigating the effects of psychomotor training with the updated VR-based haptic system.

2. Design proposal

The proposal for enhanced features as part of the VR simulator included dividing the forms of aiding in two categories: haptic and visual. Haptic features implemented in the Year 2 study can be categorized as virtual fixtures (VF), a form a penalty-based haptic feedback that helps users maintain a desired trajectory of motion by activating in response to errors (Rosenberg, 1993). There are numerous options
for implementing virtual fixtures. For example, Basdogan et al. (2007) combined multiple haptic features in a system providing assistance to control tweezers during an assembly task. Feedback forces were presented in the form of virtual boundaries to help users move small particles along optimized trajectories. The specific forces presented to users through the haptic device included: (1) penalty-based guidance forces to keep users on an optimal path, (2) a drag force when users moved too fast, and (3) a snap effect to indicate the end of the path. The snap effect completed the movement by pulling the particle into the target when it was within close range. Motor assistance in the VR BD task developed as part of the Year 2 research likewise included snap forces and rejection forces at blocks during pattern reconstruction. The snap force was expected to assist users by prompting the correct movement when approaching the target position at close range. It was designed to reinforce correct placement of blocks and reduce the need for additional visual verification. The rejection force was designed to reveal block placement errors. In the Year 2 study, the rejection forces made incorrect block placement impossible, which inflated task scores for the augmented VR condition.

On this basis, the proposed enhancements to the simulator in terms of haptic features included reducing block rejection forces to allow for incorrect placement or user errors under the augmented VR condition. The team proposed designing rejection forces based on average approach speed and force during correct placement. The idea was to provide haptic feedback that would prompt participants to verify block placement without preventing block placement completely. These forms of scheduled haptic feedback were intended to limit self-appraisals of performance and to make operators less dependent on the haptic features for task performance. Both forms of haptic assistance were designed to assist users passively (i.e., without additional voluntary control of the haptic device). These features were ultimately included in the enhanced version of the VR system for the Year 3 research.

The proposal for the visual features, in contrast to the passive haptic features, initially required users to request assistance explicitly. Proposed visual assistance included the use of a grid to segment design patterns for trainees and pattern highlighting. The proposal included drawing a grid over the stimulus design, revealing the positions and orientations of each block in a pattern. This feature was expected to help users identify individual blocks within a design, but at the cost of additional task time while activating the assistance. It was expected that users would decrease their dependency on this function as their capability to mentally parse patterns increased over time, which would provide additional evidence of learning. Pattern highlighting was proposed to reveal the position and orientation of a single block in the design (i.e., a square) as well as any matching block faces in the task work space. The highlighting was expected to help identify individual block placement solutions. These cues would be triggered by touching a specific element within a pattern and would remain active until a block was placed on the work surface. Similar to grid highlighting, this feature would also require users to explicitly invoke the assistance.

Additional features were proposed based on observations made by the project team during the Year 2 experiment data collection. To be consistent with the design proposal, the issues identified by the project team were divided into haptic and visual-spatial categories. They were as follows:
**Improve block rotation.** The main feature problem observed by team members was that experiment participants had difficulty grasping and rotating the pen-like stylus more than 90 degrees at the wrist, which limited block rotation. Figure 1 (a) illustrates that, when gripping the stylus, the maximum pronation angle is less than 90 degrees from a normal handwriting posture position. Reorientation of the stylus was not possible because participants were required to hold a control button on the stylus with the index finger while manipulating each block. These issues resulted in excessive fatigue or participants reorienting blocks by repeatedly picking them up and putting them down, which increased task time. The first design enhancement for block rotation, therefore, was to optimize the control-to-response (C/R) ratio (gain) of the haptic device to reduce the block rotation challenge. Two levels, 1:2 and 1:3 were implemented for usability testing. The gain levels meant that a 90 degree wrist rotation would translate to 180 or 270 degrees of block rotation (see Figure 2 (a)). The second enhancement related to block rotation was to allow users to roll a block by pushing the cursor or proxy for the haptic device against a block resting on the worksurface. The rolling direction was determined based on the cursor’s swipe direction. Blocks could be rolled upward and downward (roll and pitch) through swiping. Perpendicular rotation could be performed by pressing the stylus button while touching the cursor to a block (yaw). When the button was pressed while the cursor was touching the top of a block, the block would be rotated 90-degrees.

**Grasp block by contact.** Another haptic usability problem that was observed by team members occurred due to the need for users to hold down a button on the stylus while manipulating blocks. The original concept was that pressing and releasing the button would represent a pinch grip. Unfortunately, the button on the stylus was not large enough to be easily located and held by a finger, and the requirement for constant pressure at the button increased fatigue. Figure 1 (b) presents the button and hand grip. The grasping mechanism was simplified to address this problem. Instead of holding the button, a block could be grasped by briefly touching the cursor to it. The block was automatically returned to the work surface when it came into contact with the virtual table.

**Highlight grid.** The first of the observed visual-spatial problems suggested that field dependent (FD) users might have difficulty recognizing how individual block position and orientation in a grid pattern contributed to the overall design (Figure 1 (c)). This issue has also been identified by prior research (Witkin & Goodenough, 1981). With respect to the present program of NSF research, there was a concern that the maximum learning the effect of motor skill training could not be achieved by FD users due to excess cognitive effort associated with the VR interface. To solve this problem, users could superimpose a virtual grid on the stimulus figure to reveal the BD construction. Touching the stimulus figure with the cursor for the haptic device would activate this form of assistance. The grid would then continue to appear briefly once every 3 seconds until turned off by touching the stimulus with the cursor a second time. These types of aids help parse the stimulus design into elements. Prior research has considered this to be the most time-consuming cognitive aspect of the BD task (Rozencwaig & Corroyer, 2001).

**Transparent blocks.** Due to limitations on perspective views in the VR, team members expressed concerns that users might not be able to develop accurate internal representations of block
configuration. In native BD task performance, trainees could move their heads or perform subtle wrist motions to alter their perspectives of the blocks. The VR did not support these types of dynamic viewing and, therefore, task performance time was increased. To resolve this, blocks were made translucent to reveal the patterns on every side. Grasped blocks would become translucent and then return to normal (opaque) when returned to the work surface.

Figure 1. Interface features observed during usability testing.

Figure 2. Enhanced simulation design features.
**Auditory feedback.** Even though the virtual environment (VE) system was capable of providing extrinsic multi-modal feedback, which has potential to support greater motor learning (Van Vliet & Wulf, 2006), the system developed in Year 2 did not incorporate auditory feedback. Therefore, system design improvements also included new audio cues to reinforce the haptic and visual features. Audio cues were designed to accompany basic environmental events including contact between the cursor and the blocks, contact among blocks, and contact between the blocks and the work surface. The audio cues were implemented in all conditions.

3. **Literature review and task strategy analysis**

The visual aiding design proposal was intended to improve the performance of FD users. Field dependence and field independence (FID) refer to whether an individual tends to perceive perceptual fields as combined (FD) or discrete parts (FID; Witkin & Goodenough, 1981). Field independent individuals are more skilled at selecting parts of a perceptual field than are FDs (Doucette, Kelleher, Murphy & Young, 1997). It was expected that FD participants would not be able to parse the block design patterns into discrete squares as effectively as FID participants; therefore the visual assistance was designed to perform the step of visually parsing the stimulus figure for users.

The Group Embedded Figures Test (GEFT; Witkin et. al., 1971) is used to assess field dependence/independence behavior. The GEFT requires participants to identify and trace a series of simple figures concealed within more complex ones (Day et. al., 1990). Scores range from 0 to 18, with higher scores representing FID behavior. This test was consequently added to the test battery for the Year 3 study. The results of the test were used to identify participant perceptual style and confirm whether visual assistance revisions helped participants who experience difficulty decomposing the stimulus design.

To further validate the VR simulator design revision, the research team prepared a cognitive task analysis of the BD task identifying how specific design modifications would be compatible with task procedures. As a basis for this analysis, the team again consulted available literature on the BD task to determine what strategies participants use to complete the various designs. In one study, Hoffman et al. (2003) identified a series of five steps participants use to construct the designs, including:

1. looking at the model to gain information about its spatial organization;
2. searching the task workspace for a block that matches one component of the model organization;
3. reexamining the model to see where to place the block;
4. checking the model to verify that the copy matches it;
5. correcting the copy by removing incorrect blocks, if a discrepancy is detected; and
6. returning to Step 1 until the copy is complete.
These six steps were used as a baseline BD procedure that the project team expanded by integrating the proposed haptic and visual features in the VR system. Appendix A includes flowcharts that graphically apply Hoffman et al. steps to the VR version of the BD task with the proposed haptic (A.1) and visual (A.2) aids. The specific aids are included in the gray boxes. Appendix A.3 shows the cognitive task flow with the combination of haptic and visual aids.

The cognitive task flowcharting revealed that the visual and haptic assistance would be most applicable during the block placement step. However, implementing passive haptic assistance and active visual assistance would introduce a performance disadvantage to visual users due to the additional time required to activate the aiding. It was, therefore, determined that assistance replicating the feedback loop (Step 4) should be passive. Additional analysis of the flowcharts suggested that although the subtask decomposition was accurate, the order of completion may not be consistent with expert experience. For example, high performing users may not need a feedback loop to confirm block placement. Consistent with this observation, the BD test subjects recruited by Hoffman et al. (2003) included children and impaired adults, who do not score as high as healthy adults in the BD task and may, therefore, implement different strategies.

Previous studies have broadly categorized adult strategies used to complete BD designs as “analytic,” “synthetic,” or “global” (Rozencwajg & Corroyer, 2001; Schorr, Bower, & Kiernan, 1982). Test subjects who employ an analytic strategy mentally segment each design into squares corresponding to block faces and place each block directly to match the squares. Test subjects employing a global strategy, in contrast, tend to view the design as a whole (complete form), as opposed to individual squares. These individuals tend to reorient each block through trial and error until they match the design (Rozencwajg and Corroyer 2000). Hoffman et al. (2003) say a global strategy is more commonly used by children and characteristic of subjects having completed fewer designs. The synthetic strategy is somewhere in-between analytic and global, as test subjects perceive the complete figure as being constructed of gestalts (i.e., groups of blocks that form an easily recognizable geometric figure such as a triangle or diamond). Evidence of the contrasting approaches dates back over 70 years (Schorr, Bower, & Kiernan, 1982).

During the Year 3 experiment, we provided a questionnaire designed to determine if participants were using global, analytic or synthetic strategies to perform the BD task. However, early observations by the experimenters suggested the questionnaire would not be reliable, and the team agreed that the literature should be consulted further to identify an objective measure of strategy. Schorr et al. (1982) performed a series of four studies establishing that analytic approaches are associated with higher levels of efficiency when completing the BD task. They found that when adjacent blocks form larger shapes (i.e., gestalts), test subjects must mentally segment the shape before identifying a corresponding block face or combination of block faces. Therefore, larger gestalts require increasing segmentation, which can be achieved more effectively with an analytic approach. Rozencwajg and Corroyer (2001) expanded on Schorr et al. (1982) research by studying strategy in a two-dimensional computer-based BD task. Although the key contribution of their work was to identify developmental patterns using the BD task, many aspects of the study are relevant to the present work. The researchers defined four task “behavior indices,” including “segmentation,” “orientation,” “placement order” and “consultation frequency” in
order to identify strategies used by participants. Segmentation measures the number of corrections made during design construction. Orientation, a finer measure than segmentation, is a count of the number of attempts required to place a single block in a proper position. Placement order tracks block placement patterns during design construction, and design consolation is the number of times the test subject refers to the stimulus design (visually). Based on these indices, the researchers created a profile of an analytic strategy characterized by: (1) a high segmentation index, (2) a high orientation index, (3) high consultation frequency, and (4) placement order according to rows and columns.

The VR-based version of the BD task automatically generates user performance data files. These files were analyzed to determine which task strategies could be measured with the existing data. The team also sought to determine the strategies that were favored by system users under each aiding condition and to provide a basis for future modifications to aids to target specific strategies. The project team reviewed strategy profiles in terms of the indices defined by Rozencwaig and Corroyer (2001) and made comparison of them with the data recorded by the VR simulation software. The comparison provided a basis for determining how test subject strategies could be assessed objectively. Consultation frequency was not used to identify strategies as the index could not be obtained directly from the data files. However, the index could be determined based on post-test review of subject video recordings. Placement order was also not implemented in the analysis as it was determined that an analytic strategy (i.e., one in which the test subject is able to visualize an individual block within a design) may not necessarily manifest itself in the form of row/column placements of blocks, as suggested by Rozencwaig & Corroyer (2001). In general, an analytical strategy may be revealed by some “regular” placement order of blocks.

A simple analysis was performed to calculate the average orientation index for all participants in the Year 3 study, aggregated by condition and by trial. Results showed a possible performance difference between the three conditions, with the visual condition producing the highest index, and the haptic condition producing the lowest. This suggests visual aiding may help users implement aspects of the analytic strategy more than the other conditions. The average orientation index across all trials was consistent with the results reported by Rozencwaig & Corroyer (2001). This agreement with the existing literature suggests the orientation index may be a suitable method for objective assessment of user BD task strategy in future studies.

4. Usability test

Four expert VR users (2 males and 2 females) participated in the usability test. The test was designed to identify the enhanced system features to be used in the Year 3 experimental study. All test participants had extensive prior knowledge of the original training system. The participants were asked to evaluate the usefulness and effectiveness of the redesigned system. A survey was used (see Appendix B), including 20 questions on the various features as part of the redesign proposal. Each question was presented with a 7-point rating scale of agreement/disagreement (ranging from 1=Strongly Disagree to 7=Strongly Agree). The survey also requested general comments on the four new forms of aiding. The
participants completed predefined scenarios with the VR BD simulation. Each scenario was designed to incorporate all the new features. There was no time limit, and participants were encouraged to think aloud and ask questions during testing.

4.1. Results

The results of the usability test are summarized in Table 1.

Table 1. Usability test results.

<table>
<thead>
<tr>
<th>Usability Issue</th>
<th>Feature</th>
<th>Survey Question</th>
<th>Agreement Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block rotation</td>
<td>Decreased C/R ratio</td>
<td>Allowed blocks to be easily rotated into position.</td>
<td>6.25</td>
</tr>
<tr>
<td>Block grasp</td>
<td>Grab block by contact</td>
<td>Allowed for blocks to be easily picked-up.</td>
<td>4.5</td>
</tr>
<tr>
<td>Stimulus configuration</td>
<td>Highlighted grid</td>
<td>Made clear individual block placement and orientation in stimulus figure.</td>
<td>3.25</td>
</tr>
<tr>
<td>Block visibility</td>
<td>Transparent block on contact</td>
<td>Partially transparent wireframe made block configuration clear.</td>
<td>3.25</td>
</tr>
<tr>
<td>Multi-modal Feedback</td>
<td>Auditory Feedback</td>
<td>Provided motivating cues</td>
<td>4.75</td>
</tr>
<tr>
<td>Block rotation</td>
<td>Rolling Block</td>
<td>Allowed blocks to be easily rotated into position.</td>
<td>4.75</td>
</tr>
<tr>
<td>Block rotation</td>
<td>Button Rotation</td>
<td>Allowed blocks to be easily rotated into position.</td>
<td>2.50</td>
</tr>
</tbody>
</table>

The increase in control gain for the haptic device received the highest rating among the proposed system enhancements. Users unanimously agreed that the feature was helpful in terms of shortening task completion time and promoting convenience of hand grip. The average agreement score across the C/R ratio settings was 6.00 (SD = 0.96). Most users preferred the 1:2 C/R ratio, while one preferred the 1:3 ratio (M = 2.0, SD = 2.83).

User opinions were divided on the simplified block grabbing mechanisms. Two agreed that it was easier to pick-up a block without pressing a button; whereas, the other two disagreed (M = 4.5, SD = 2.89). However, three users reported inadvertently moving blocks due to accidental contact with the cursor, which they found frustrating.

The flashing grid was not considered useful for design pattern reconstruction. Users generally felt the grid was distracting (M = 3.25, SD = 2.06); however, they also believed that it could help FD users recognize block arrangement within the stimulus pattern (M = 5.0, SD = 1.91). One user commented that the visual aids might be helpful for novice users but distracting for experts. Another user raised a concern about increased movement time to complete the task because of the additional time required to show and reveal the grid aid.
The block transparency also produced negative user responses. Users did not feel transparent blocks helped them recognize patterns (M = 3.25, SD = 1.89), and the aid was not considered to effectively communicate block configuration (M = 2.75, SD = 2.22). One participant observed that the transparent blocks were more distracting compared to opaque blocks. Another user did not understand the intent of the transparent block design.

The block rolling feature was considered to be useful (M = 4.75, SD = 1.73). However, users felt that the feature required additional training (M = 3.75, SD = 2.22). Two users commented it would have been better to allow for block rotation about all axes. Recall that the rolling feature was only implemented for pitch and roll and not yaw.

Users did not agree that the button rotation feature facilitated easy block rotation (M = 2.5, SD = 1.73). They also felt that it took a while to become accustomed to the feature (M = 4.5, SD = 2.83). One user mentioned that the grasp process was simple but not intuitive. Another user was concerned about confusion using the button both for rotation and grasping.

4.2. Discussion

From the results of the usability survey, system performance problems related to haptic input and feedback appeared to be reduced to a greater extent by the enhanced features than problems related to visual-spatial comprehension of users. No users inadvertently dropped virtual blocks during the usability test trials. There was substantial improvement in user hand comfort and reduced task completion time.

Regarding the revised block grabbing mechanism (by contact), however, most participants reported inadvertently grasping blocks, which was frustrating. Therefore, the design team proposed clicking on a block (pressing and releasing the button on the stylus) instead of automatic grasping on contact with the cursor. Since this form of interface requires user action, blocks would not be grasped unintentionally. Block movement and manipulation will also be simplified by removing the need to hold the stylus button.

It was expected that the increased control gain would solve a considerable portion of usability problems relevant to the block rotation. Interestingly, the enhanced feature also reduced the limited perspective viewing problem. By promoting ease of rotation of blocks with the stylus, users were able to more quickly view opposite sides of a block and to form an accurate internal model of block configuration. Rolling the blocks by swiping with the cursor was also implemented, but not with a button press. Button use was restricted to block grasping.

Although most users found the superimposed flashing grid to be distracting to task performance, some agreed that novice or FD users might benefit from the aid. To maintain the potential benefits while reducing any visual distraction, the design team proposed to only present gridlines around a single block in the stimulus figure when selected by a user. Since gridlines are only shown following user input, FID (field-independent) users may not be distracted by this implementation.
4.3. Enhanced feature selection

On the basis of the initial design proposal, the literature review, VR BD task strategy analysis and the usability test results, the project team identified a select set of enhanced features for the VR system to be tested in the Year 3 experiment. Some features were included in both conditions; others were unique to the haptic and visual conditions, respectively.

4.3.1. Common features

Auditory cues
Sounds accompanying grasping, placing, and aligning blocks were included. Warning sounds were also implemented to accompany resistive forces for the haptic conditions.

Control gain
A 1:2 control-response ratio was implemented for block rotation. This meant that a 90 degree wrist rotation would translate to a 180 degree block rotation.

Grasp by button click
Blocks could be grasped by pressing the cursor against them and briefly pressing and releasing the button on the stylus. A block could be returned to the work surface by contacting it to the virtual task table.

Rolling blocks
Blocks could be rotated by swiping them with the cursor without grasping.

4.3.2. Haptic aiding

Snap force / Rejection force
Snap and rejection forces were reduced to allow incorrect block placement in the haptic conditions. This enhancement was also intended to cause comparable error rates across the native task and augmented VR conditions.

Automatic alignment force
Since the haptic device integrated with the VR BD task simulation only provided force feedback along three axes of translation, block rotation (i.e., roll, pitch and yaw) could not be communicated haptically. To account for this, blocks were automatically aligned with the grid as they were moved toward the construction area.

4.3.3. Visual aiding

Highlighted blocks
In the augmented VR system, a target grid was presented in the BD workspace (see Figure 3 below). If a user attempted to place a block in an incorrect orientation in the target grid, a yellow “X” or an arrow would be superimposed on the block. The “X” would appear when the wrong block face was showing (see Figure 3 (a)). The arrow would appear when the correct block face was showing, but it was rotated...
incorrectly (see Figure 3 (b)). The arrow indicated the direction in which the block needed to be rotated for correct orientation in the target grid square. If a user moved a block in the correct orientation over the grid, those squares in the grid at which the block could be placed without error would be highlighted in yellow for the user (see Figure 3 (b)).

(a) Indicating “X” when the wrong block face is shown.  
(b) Indicating “Arrow” when the block needs to be rotated for correct orientation in the target grid square.

Figure 3. Visual assistance during block placement.

Highlighted Grid
Users could also receive hints as to how to correctly place blocks by touching the cursor to the stimulus design at the top of the screen or the target grid. These hints were designed to reveal the orientation and locations of individual block faces. Touching the cursor to a target grid square would highlight the corresponding square in the stimulus design and any blocks matching the selected square (Figure 4). Likewise, touching the stimulus design would highlight the corresponding square on the target grid. The gridlines disappeared when any surface outside of the stimulus figure and grid was contacted with the simulation cursor.

Figure 4. Grid and block highlighting.

After the above features were implemented and the VR training simulation was validated through pilot testing, the Year 3 study was carried out.
5. Experimental study

5.1. Participants

Twenty-four participants between the ages of 18 and 44 were recruited for the study. All participants were required to have 20/20 (or corrected to normal) vision and to exhibit right-hand dominance. These numbers and demographic requirements were the same as for the Year 2 study. Right-hand dominance was identified through a demographic questionnaire and confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were required to complete all motor tasks as part of the experiment using their non-dominant (left) hand. This requirement was meant to simulate a minor motor impairment and to disadvantage participant task performance in order to promote sensitivity to the training conditions. Both the questionnaire and inventory were administered with electronic forms prior to a participant visiting the research lab for training.

5.2. Apparatus

The experiment utilized the same computer hardware and physical workstations as the Year 2 study. The VR interface for the BD task was presented on a PC integrated with a stereoscopic display using a NVIDIA® 3D Vision™ Kit, including 3D goggles and an emitter (see Figure 5 (a)). Stereoscopic rendering of the task simulation was supported by an OpenGL quad buffered stereo, high-performance video card (NVIDIA® Quadro™). A SensAble Technologies PHANTOM Omni® Haptic Device was used as the haptic control interface. The Omni includes a boom-mounted stylus that supports 6 DOF movement and 3 DOF force feedback. The interface recorded participant performance data automatically. The ROCF reproduction task interface was designed to replicate a drawing setup. It included a custom workstation featuring a flat-screen monitor mounted in a tabletop and an Omni Haptic Device (see Figure 5 (b)). To perform the ROCF (see the bottom-left of Figure 5 (b) for the ROCF image), participants used the Omni to virtually draw the complex figure elements directly on the horizontally-aligned monitor while the simulation recorded participant performance data automatically.
The software used in the present study was an updated version of the VR simulation of the WASI BD subtask from Year 2. As before, the VE features included a virtual tabletop divided into two parts, including a display area (see Figure 6 (a)) and a work area (see Figure 6 (c)). The display area presented the stimulus design pattern (see Figure 6 (b)) to be replicated by a participant. The work area was used for arranging the blocks. The work area and blocks were presented at approximately 70% of actual size to allow the design pattern and workspace to be viewed on a 21-inch stereo monitor. All BDs were constructed with the aid of the new target grid (see Figure 6 (d)), which appeared as a 2x2 or 3x3 collection of squares in the work area, depending on the design stimulus.

The Omni haptic device was used to manipulate a cursor appearing on the display during BD training. Blocks could be grasped by touching the cursor against them and pressing the button on the stylus of the haptic device. A block could then be lifted from the table surface and rotated along any axis using the stylus. Some haptic features were included to represent the blocks and the table as solid objects.

5.3. Testing

The test software and hardware were separate from the training apparatus (described above). Baseline and post-experiment testing were conducted in order to measure the effects of the BD task therapy by
using two commercially available psychomotor tests, including the ROCF copy test and the BD subtest from the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III; Wechsler, 1997). The WAIS BD task used for testing and the WASI BD task used for training are identical except for the stimulus design patterns. During testing, the WAIS BD subtests were administered using standardized materials. Block design scoring is based on a combination of speed and accuracy. Adult participants are automatically awarded 12 points for successfully completing the test, and scores between 0 and 7 are awarded for each design for a total score ranging between 12 and 68.

The ROCF was administered using a VR adaptation of the task developed in a previous study (Li et al., 2010). Rey Osterrieth Complex Figure performance is scored by evaluating 18 individual components of the figure that make up a complete design, referred to as units, on a scale from 0 to 2 in terms of accuracy (e.g., size, length) and placement (e.g., proximity to other units). The sum of the scores for the 18 components is calculated for a total score between 0 and 36.

The GEFT was administered to assess field dependence/independence. A detailed description of the test procedure is provided in Appendix C.

5.4. Dice motor skill training program

In the Year 2 study, we observed substantial learning during VR training, and it was assumed that some portion of this learning included the participants becoming proficient with the haptic device. To limit this aspect of the learning, we developed a separate simulation designed to train participants with the haptic device, incorporating movements necessary in the BD task, but without providing additional insight into the BD task.

5.4.1. Description

The training VE included a single virtual die placed near the center of the work surface and a square near the right side of the work surface. A 2-D image of a single side of a die (stimulus) was presented at the top of the screen in the display area. (See Figure 7) The goal of the task was to move the die as quickly and accurately as possible to the target square. The top surface of the die had to match the stimulus.

The task was developed using the same development environment as the VR-BD task. Therefore, user interactions (e.g., block grasping and release, collisions, sounds, lighting) were basically the same. All dies were colored yellow to differentiate them from the white and red sides of the BD blocks. Other than this difference, the colors of the two VEs were the same.
A die was chosen for its practical similarity to the red and white blocks used in the BD task. Both objects are cubes, so visibility is similar for each. Furthermore, both have sides featuring patterns that may or may not depend on the cube’s orientation. For example, a solid white side appears the same regardless of how the block is rotated. In contrast, a rotation is apparent when a mixed white/red side is showing (see Figure 10 for example). Finally, dice are familiar objects to many people.

The virtual die was modeled after a precision die in a clockwise arrangement. This means that opposite sides always sum to seven, and the 1-3 sides are arranged clockwise around a common corner. Figure 8 shows the configuration of the virtual die when unfolded.

**Training procedure**
The dice training task included four levels of difficulty, which were based on the orientation and rotation of the die necessary prior to placement on the target. For the first level, the target side of the die appeared face-up when the die was in the starting position. Furthermore, the target side did not require a specific orientation. The starting position of the die was randomly determined within a defined X, Y plane on left side of the work surface. In this context, “target side” refers to the side of the die facing up when the die is placed on the work surface. The number of dots appearing on the target side determined specific orientations. Sides with 1, 4, or 5 dots are orientation independent, while sides with 2, 3, or 6 dots are orientation dependent (i.e., a side with 4 dots appears identical when rotated 90 degrees, but a side with 3 dots will slant upward or downward when rotated 90 degrees). Therefore, at Level 1, the participant only had to grasp the block and relocate it within the target square without a rotation. At Level 2, the target side was face-up when the die was in the starting position, but the die required a specific orientation and was offset by 90 degrees. Therefore, the participant had to rotate the top surface of the block prior to placement. At Level 3, the target side was offset by 90 degrees when the die was in the starting position and the target side did not require a specific orientation. At this level,
the participant had to locate the target side while moving the block; however, the final orientation was always correct (i.e., the target side was a 1, 4 or 5). At Level 4, the target side was offset by 180 degrees when the die was in the starting position, and the target side required a specific orientation. Therefore, the participant had to rotate the block to the opposite side during movement and place the block in a specific orientation. The four levels of training task difficulty are summarized in Table 2.

Table 2. Dice training scenarios.

<table>
<thead>
<tr>
<th>Design</th>
<th>Orientation</th>
<th>Target side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>Flexible</td>
<td>Same</td>
</tr>
<tr>
<td>Level 2</td>
<td>Fixed</td>
<td>Same</td>
</tr>
<tr>
<td>Level 3</td>
<td>Flexible</td>
<td>Adjacent</td>
</tr>
<tr>
<td>Level 4</td>
<td>Fixed</td>
<td>Opposite</td>
</tr>
</tbody>
</table>

The software automatically measured the distance from starting point to the target, the velocity of die movement, and deviation of the die from the target square (in distance and degrees of rotation) upon placement. The velocity of movements was calculated based on the time required to move the die from the starting position to the target square. A trial ended as soon as the die was placed, and the deviation results were presented to participants (see Figure 9).

During training, participants performed trials at levels of difficulty 1-4 in ascending order. After completing the first four trials, Levels 3 and 4 were repeated until the participant completed 40 trials. The number of trials was determined based on asymptotic performance levels identified following pilot testing. During data collection, training was terminated after 40 trials or when participant performance reached expert-level performance (based on velocity and accuracy), whichever occurred first.

![Figure 9. Dialog indicating task completion.](image)

5.5. Video training

Training videos were also created to provide participants with identical training experiences. Separate videos were created for each test condition. The videos were presented prior to the BD training.
sessions. The videos included descriptions of the VR system and the VE as well as demonstrations of block movement, grasping and rotation. Table 3 shows the URLs for each training video, which are all accessible online (as of June 1, 2012).

**Table 3. Video training links.**

<table>
<thead>
<tr>
<th>Training Module</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dice training</td>
<td><a href="http://www.youtube.com/watch?v=C281Ql2vtEU">http://www.youtube.com/watch?v=C281Ql2vtEU</a></td>
</tr>
<tr>
<td>Haptic condition</td>
<td><a href="http://www.youtube.com/watch?v=0CUOKQcDZE">http://www.youtube.com/watch?v=0CUOKQcDZE</a></td>
</tr>
<tr>
<td>Combination (haptic &amp; visual conditions)</td>
<td><a href="http://www.youtube.com/watch?v=iRI8WQvT3Ds">http://www.youtube.com/watch?v=iRI8WQvT3Ds</a></td>
</tr>
</tbody>
</table>

### 5.6. Block Design training

The BD test evaluates visuo-spatial and motor skills by requiring participants to build replicas of multiple block patterns. Participants are given a set of nine identical red and white blocks printed with either solid or cross-sectional patterns on each side (see Figure 10 for image of native BD task materials). They are asked to replicate complex designs shown in a series of test cards. Scoring is based on speed and accuracy. The subtests of the WASI are based on the WAIS-III; therefore, the procedures and materials for the WASI version of the BD test are nearly identical to its WAIS-III counterpart. As previously mentioned, the main difference between the two versions of the test is the use different stimulus figures. For the present study, we used the WAIS-III BD test to measure training effects following repeated WASI BD trials.

![Figure 10. Native BD task materials](image)

### 5.7. Experiment procedures

Experiment sessions were designed to simulate occupational therapy to promote psychomotor skill development. The ROCF and WAIS BD task represented occupational tasks anticipated to improve as a
result of therapy. These two tests were administered once prior to training to evaluate baseline psychomotor performance and again following multiple psychomotor training sessions in order to measure performance improvements.

There were three main parts of the experiment for data collection: (1) an evaluation of baseline performance, (2) multiple training sessions, and (3) the post-test to measure improvement. The three parts of the experiment were distributed across four days, as presented in Figure 11. Each participant committed a total of 5 hours to the study.

![Figure 11. Overview of experiment schedule](image)

Training was facilitated through the BD VR task with one of three types of aiding, either haptic, visual, or a combination of haptic and visual. Each participant was assigned to one aiding type yielding a total of eight participants per condition. Each participant visited the research lab for three separate training sessions, completing eight BD trials in total (10 designs per trial as required by the established WASI protocol). The combined duration of the three visits was approximately 3 hours. The duration of the motor-skill training was established through pilot testing prior to the Year 2 study.

5.8. Experiment conditions

**Condition 1: Haptic**
The haptic-aid condition included the features described in Section 4.2.

**Condition 2: Visual**
The Visual condition is described in Section 4.3.3.

**Condition 3: Combination**
The combination condition combined the haptic and visual features.
5.9. Variables

The independent variable manipulated in the study was the type of aiding: (1) haptic, (2) visual, or (3) combination. The dependent variables included: (1) WAIS BD test performance; (2) ROCF test performance; (3) the BD task completion time during training; (4) learning percentage calculated based on BD task completion time during training; and (5) GEFT scores. With respect to the WAIS BD and ROCF test performance, we determined the percent change in test scores from baseline to post-test (i.e., (2) - (1)) using the following formula:

Percent improvement = ((Post-test Score – Baseline test Score) / Baseline test Score) x 100

The BD performance during training was collected to allow for assessment of the impact of the VR-haptic interface on task/training performance. Subjective confidence ratings (CR) of ROCF test accuracy were also collected during the first and final sessions of the experiment. More details on the response measures are provided in the results section.

5.10. Hypotheses

In general, we hypothesized that all three VR conditions would result in ROCF and BD test performance improvements (Hypothesis (H1)). Based on the results of the Year 2 study, it was expected that training in the combination condition would result in greater improvements in ROCF performance as compared to visual or haptic aiding, alone (H2). Haptic cues, including those presented as part of the combination condition, were expected to result in greater ROCF test improvement, and visual cues, including those presented as part of the combination condition, were expected to facilitate greater BD test improvement (H3). Visual cues were expected to provide greater benefits to FD participants and improve BD performance during task training and testing (H4).

5.11. Data analysis

Based on GEFT test scores, subjects were classified into one of three FID levels (i.e., high, medium, low). Participants with ‘high’ scores were labeled as FID and ‘low’ scoring participants were identified as FD. The ‘medium’ group results were not used in examining the relation of perceptual style to training or test task performance.

The statistical tests used in the data analysis were as follows:

- Shapiro-Wilks’ test was applied to check the normality of the data distribution.
- Paired t-test and Wilcoxon rank sum tests represented parametric and nonparametric methods for paired comparisons.
- One-way analyses of variance (ANOVAs) were a parametric test applied to check the effect of the experiment conditions.
- Tukey’s Honestly Significant Difference tests were applied for post-hoc analysis of significant results.
• Kruskal-Wallis (nonparametric) tests were applied to check the effect of the experiment conditions.
• Analysis of covariance (ANCOVA) was applied to check the effect of the experiment conditions when considering another variable as covariate. (Tukey’s HSD tests were also applied to significant ANCOVA results.

5.12. Results

Training and pre- and post-test data were analyzed to identify differences among the three conditions. A series of one-way nonparametric Kruskal-Wallis tests were conducted comparing differences between pre and post-test scores. This nonparametric version of the ANOVA was used due to the small sample size collected for each of the condition groups (i.e., 8). Learning percentage (K) based on the BD completion time and BD errors were used to investigate the effects of test conditions on the training scores. The ANCOVA was used to investigate how the training and pre- and post-test data were related to the GEFT scores (i.e., FD or FID). That is, the effect of the different training conditions on test performance may have been mediated by perceptual style. The results are summarized in the following sections.

5.12.1. Change in pre- to post-test performance

The baseline performance (i.e., ROCF and BD pre-test scores) of participants assigned to the three different training conditions was compared using Kruskal-Wallis tests. Tests did not reveal significant differences attributable to the training condition. In other words, participants began data collection at similar performance levels across conditions.

The scores and percent change (improvement from baseline to post-test in all cases) for each training condition are summarized in Table 4.

<table>
<thead>
<tr>
<th>Condition</th>
<th>N</th>
<th>ROCF</th>
<th>CR</th>
<th>BD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>% Improv.</td>
</tr>
<tr>
<td>Comb.</td>
<td>8</td>
<td>25.75</td>
<td>28.25</td>
<td>13.84</td>
</tr>
<tr>
<td>Haptic</td>
<td>8</td>
<td>27.00</td>
<td>28.13</td>
<td>7.63</td>
</tr>
<tr>
<td>Visual</td>
<td>8</td>
<td>24.63</td>
<td>28.19</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Note: % Improv. = Percent improvement in test score

Pre- and post-test scores were subsequently compared for each training condition. As a result of some of the response data violating the normality assumption of parametric tests, Wilcoxon rank sum paired tests were conducted on the various conditions. The p-values are summarized in Table 5. Participant BD test scores as well as confidence ratings improved significantly as a result of all three training conditions. However, ROCF test performance did not reveal significant improvements from baseline to post-
training. Only participants assigned to the visual condition showed marginally significant improvements in ROCF scores \((p=0.061)\). Analysis of ROCF completion times showed participants trained in the haptic condition to achieve significant reductions in the time required to complete the ROCF test \((p=0.039)\). Additional analysis on the percent change in test scores showed increases in BD and CR scores there were no significant differences in the extent of improvement among training conditions. Although the three conditions resulted in similar increases, on average, the haptic condition showed the highest percentage of BD test and CR improvement.

Table 4. P-values for differences in pre- and post-test results.

<table>
<thead>
<tr>
<th>Condition</th>
<th>ROCF Score</th>
<th>CR</th>
<th>BD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination</td>
<td>0.200</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>Haptic</td>
<td>0.288</td>
<td>0.011</td>
<td>0.007</td>
</tr>
<tr>
<td>Visual</td>
<td>0.061</td>
<td>0.017</td>
<td>0.018</td>
</tr>
</tbody>
</table>

5.12.2. Learning percentages for training sessions

The BD task learning percentage \((K)\) based completion time and errors \(\text{(i.e., full score – actual score)}\) were calculated for each participant. The \(K\)-value means and standard errors for each condition are summarized in Table 6. It is most important to note that lower \(K\)-values indicate a higher potential for future learning in the task \(\text{(i.e., faster learning speed)}\).

Table 6. BD training \(K\)-values by condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>(N)</th>
<th>K for BD completion time ((\text{mean (std)}))</th>
<th>K for BD error ((\text{mean (std)}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination</td>
<td>8</td>
<td>80.13 (1.512)</td>
<td>88.80 (3.712)</td>
</tr>
<tr>
<td>Haptic</td>
<td>8</td>
<td>75.47 (1.471)</td>
<td>84.85 (0.921)</td>
</tr>
<tr>
<td>Visual</td>
<td>8</td>
<td>77.96 (2.929)</td>
<td>89.61 (2.980)</td>
</tr>
<tr>
<td>Native</td>
<td>8</td>
<td>79.95 (2.937)</td>
<td>54.70 (2.774)</td>
</tr>
</tbody>
</table>

\(K\)-values based on BD task time did not reveal any significant effects due to condition \((F(3,28) = 0.874, \ p = 0.466)\). However, the \(K\)-values based on the BD error levels were found to be significantly different \((p < 0.001)\). Post-hoc analysis, using Tukey’s HSD test showed a significantly lower \(K\)-value for the Native condition \((p < 0.05)\), as compared with the VR conditions. Although there were no significant differences among the three VR conditions, the haptic condition showed the best learning potential in terms of both completion time and task errors as compared to the other conditions.

5.12.3. Field dependence and independence in test performance

Table 7 summarizes the means and standard deviations for percent change in ROCF and BD test performance from baseline to post-training for FID and FD participants for all conditions. Due to the small sample size, the power of the statistical tests was too low to yield any reliable inferential results.
Table 8 suggests, however, that FID participants achieved greater improvements in ROCF scores as a result of training in the visual condition, and haptic cues supported greater improvement in BD scores. In contrast, FD participants achieved greater improvements in BD and ROCF scores following training in the haptic condition.

Table 7. ROCF and BD test percent improvement for FD and FID participants by condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>N</th>
<th>FID</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ROCF (%)</td>
<td>BD (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td>2</td>
<td>16.79 (15.03)</td>
<td>9.38 (4.62)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haptic</td>
<td>3</td>
<td>5.73 (4.00)</td>
<td>24.28 (13.29)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual</td>
<td>3</td>
<td>24.96 (16.92)</td>
<td>6.88 (3.67)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Block design error and BD completion time were used to assess performance during training. Figures 12 and 13 show the BD error and completion time categorized by FD and FID participants, respectively, across the eight training sessions. The difference between the first and last trial for FID participants revealed less improvement in the task performance measures, as compared with FD participants.

Figure 12. BD error and completion time across trials by condition for FID subjects.

Figure 13. BD error and completion time across trials by condition for FD subjects.
The learning percentages (K-values) for the FD and FID participants based on BD errors and completion time are summarized in Table 8. In general, visual cues were not as helpful as haptic and combination cues in assisting FID participants. Also, haptic cues led to the greatest decreases in task completion time, while combination cues resulted in the greatest decreases in error. With respect to the FD participants, however, the combination condition resulted in the best performance, although haptic cues provided the best learning potential based on both task errors and completion time.

Table 8. FD and FID participant learning percentage by condition.

<table>
<thead>
<tr>
<th>Condition</th>
<th>N</th>
<th>FID</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>FD</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K (time)</td>
<td>K (error)</td>
<td></td>
<td></td>
<td></td>
<td>K (time)</td>
<td>K (error)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td>2</td>
<td>84.23 (4.41)</td>
<td>81.17 (15.05)</td>
<td>3</td>
<td>76.58 (1.51)</td>
<td>87.41 (3.17)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haptic</td>
<td>3</td>
<td>76.49 (2.84)</td>
<td>84.13 (1.16)</td>
<td>1</td>
<td>68.98 (/)</td>
<td>83.50 (/)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual</td>
<td>3</td>
<td>78.05 (5.39)</td>
<td>92.64 (5.54)</td>
<td>4</td>
<td>76.65 (4.78)</td>
<td>87.56 (4.72)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An ANCOVA was conducted to check the training condition effect of K-values based on BD errors when considering participant perceptual style (GEFT scores) and initial task performance (BD errors in the first training trial (T1)) as covariates in the statistical model. The results shown in Table 9 reveal a significant effect of training condition on task learning percentages that is pervasive across perceptual styles and initial performance levels. Both covariates, GEFT scores and initial BD trial performance, were found to have significant influence on participant learning percentage.

Table 9. Summary of ANCOVA result.

<table>
<thead>
<tr>
<th></th>
<th>DF</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>(2,19)</td>
<td>5.97</td>
<td>0.011</td>
</tr>
<tr>
<td>GEFT</td>
<td>(1,19)</td>
<td>8.69</td>
<td>0.009</td>
</tr>
<tr>
<td>T1</td>
<td>(1,19)</td>
<td>17.04</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

To further investigate the influence of condition and the two covariates on learning percentages, Tukey’s HSD tests were conducted. Results revealed the haptic aiding condition to produce the lowest learning percentage, while the combination condition resulted in the highest learning percentage. This indicates that the haptic condition resulted in the highest potential for future learning. Furthermore, the learning percentage decreased (potential increased) as GEFT scores or T1 errors increased. These results indicate that FID participants, or participants with worse initial performance levels, would have a higher potential for future learning. Table 10 summarizes the test results on learning percentage for the different training conditions. Tukey’s test results are presented using alphabetic characters to identify groupings of condition means. Means with the same character label are not significantly different (p>0.05).
Table 5. Tukey’s test results on learning percentage.

<table>
<thead>
<tr>
<th>Training Condition</th>
<th>Least Sq. Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination A</td>
<td>92.01</td>
</tr>
<tr>
<td>Visual A</td>
<td>90.37</td>
</tr>
<tr>
<td>Haptic B</td>
<td>85.47</td>
</tr>
</tbody>
</table>

5.12.4. Highlighted grid use

The highlighted grid was triggered manually by touching the cursor to the stimulus design (see Figure 4 (b)) or the target grid (see Figure 4 (d)). Participants rarely touched the stimulus design presented at the top of the virtual table to request visual assistance. Visual aids triggered by cursor contact with the stimulus pattern appeared during only 2.8% and 0.2% of the total visual aiding time and visual and combination aiding time, respectively, during training performance. Therefore, only the use of target grid highlighting was considered in this analysis.

Results of pairwise t-tests on the number of visual aid uses revealed a significant difference between the visual only aiding and combination condition (t(127) = -2.80, p = 0.006). Visual aids were used more in the visual condition (M=13.95, SE=12.39), as compared to the combination condition (M= 9.125, SE= 6.06).

As a basis for the analysis of the influence of perceptual style (FD vs. FID) on visual aid use under the various training conditions, the response data (number of aid requests) were transformed using a log transformation. Diagnostics on the raw response measure within FD and FID groups revealed violations of the normality assumption of parametric tests. The log transformation caused the distribution of the data to more closely approximate the normal distribution, assumed by the ANOVA method.

The results of an ANOVA on the number of visual aid requests revealed a significant effect of perceptual style (F(2,125)=5.11, p=0.0074). As shown in Figure 14, the mean number of requests was higher for FD participants. Additional comparisons between the types of perceptual style using Tukey’s HSD tests revealed participants with high FD to use more visual aiding than those with moderate FD or FID participants (p=0.0125, p=0.0492). Moderate FD and FID participants were not significantly different in their use of visual aiding (p=0.9512).
5.13. Discussion

The results of the experiment revealed that training in any of the three conditions increased BD test performance, which was consistent with H1. Furthermore, training in all conditions resulted in increases in participant confidence in ROCF reproduction accuracy. However, contrary to H1, training did not necessarily lead to increases in ROCF performance. Beyond this, the degree of improvement in test task performance varied by condition. There are several possible reasons for this. The snap force feature, implemented as part of the haptic aiding condition pulled the blocks into their final position as they were moved near the design construction. In effect, the fine tuning portion of the movement from the start to end location was “offloaded” to the system, and participants were not required to perform any fine positioning. This means that conditions providing haptic assistance (i.e., the haptic and combination conditions) provided less fine motor skill training than the visual only aiding condition. These fine motor skills would be useful when replicating the ROCF using the haptic device. This may explain the marginally significant increase in ROCF scores under the visual aiding condition as well as the lack of support for H3. That is, the haptic aiding did not produce a benefit in terms of ROCF scores.

Similar results were observed following training in the visual condition. The visual aiding was designed to assist FD participants in parsing the stimulus designs into individual squares corresponding to block faces. This offloaded some cognitive aspects of the task to the system, thereby providing less training to the participant in terms of mental segmentation of a block design. There is evidence that participants receiving visual assistance relied on the automated assistance rather than honing their own cognitive skills to achieve an analytical strategy in the task. The additional visual and mental processing of a stimulus pattern required of participants assigned to the haptic aiding condition likely helped them refine their strategy for segmentation, as compared to the visually aided participants. It is likely that this
is the reason that haptically aided subjects showed the greatest increases in BD test performance and CRs. Related to this, the results on the visual aiding condition did not support H3.

This outcome is important to the ongoing system design as part of the project. While a form of aiding may be developed to help train psychomotor skills, it may also hinder development of skill requirements that are ultimately allocated to automated assistance. This raises an important distinction between designing for task performance and designing for training performance. There is evidence that the visual and haptic aids we designed to improve BD task performance during training did just that. In particular, FD participants performed the training task at levels similar to FID participants when visual assistance was available. This finding was in partial support of H4; that is, the visual aiding benefited FD participants during training. However, by offloading some cognitive aspects of the task to the automation, these participants received less training that could improve BD test scores (one of the measures of training effectiveness). This observation was counter to H4; that is, visual aiding would support FD participants in achieving greater post-test performance. Therefore, when training participants without cognitive impairments, it may be best to provide less assistance to the skill of interest so they have the opportunity to refine the skill independently.

It was expected that training in the combination condition would lead to the greatest increases in test performance due to the presentation of haptic and visual cues (H2). However, results did not support this expectation. In fact, the combination condition led to some of the worst training effects and the smallest increases in confidence ratings. This may be due to the combination of visual and haptic assistance increasing cognitive load or distracting participants during training. The combination condition also provided the greatest opportunity for participants to offload task functions to the system and increase dependency on the automation, which may have limited development of the skills needed for task performance. This situation may have led to the reduced participant confidence as compared to the other training groups.

5.14. Conclusion

The Year 3 study reinforced the results from Year 2 and further demonstrated the utility of advanced VR-based haptic simulations for training psychomotor skills. We conducted a second experimental investigation incorporating healthy participants to provide insight for the design of VR simulations to support rehabilitation of motor skills in mTBI patients. The study tested enhanced haptic and visual features in a VE developed based on previous research in the area, as well as usability tests performed on high fidelity prototypes. In general, learning rates for haptic aiding showed the best learning potential as determined based on task completion time and errors. Haptic assistance was also observed to be more helpful for unimpaired FID (field-independent) participants in improving ROCF and BD test performance.

There were some limitations to this research that will be addressed in the Year 4 study. Administering the GEFT during baseline testing led to an unbalanced number of FD and FID participants assigned to each training condition. In the future, we will use the GEFT during screening to recruit equal numbers of FD and FID participants. This procedure may also have other benefits for the recruiting effort. GEFT
performance has been shown to be related to gender. Men tend to be more FID than woman (Andrieux, 1955; Bennett, 1956). Moreover, there are many studies that have shown age-related changes in disembedding ability (Schwartz & Karp, 1967). Therefore, use of the GEFT test could help balance gender, age and FD/FID during participant screening.

In Year 4, we will continue to work with unimpaired participants, incorporating fMRI in baseline and post-test procedures. We will also recruit from a pathological population to observe the effects of VR-based haptic training on patients with a history of mTBI. The Year 4 study will be physically distributed between North Carolina State University and the Durham Veteran’s Administration Medical Center.

6. References


NCSU AND DUKE ACTIVITIES

During the third project year, the Industrial & Systems Engineering (ISE) team at NCSU (Kaber, Lee, Gil, Clamann, Jeon, Ma, Qin, Zhang and Zhu) pursued several objectives, including:

1. review of visual and haptic features as part of the prototype VR and haptic-based simulator for psychomotor skill training;
2. formulation of a design proposal for enhancement of the VR system features in terms of supporting realistic motor behavior and visual processing in complex psychomotor skill tasks;
3. usability testing of the enhanced system features; and
4. an experimental study to investigate the effectiveness of the enhanced VR simulator for training motor skills and for identifying the independent effects of visual and haptic aiding on trainee performance.

During the second project year, the Psychiatry and Behavioral Sciences team at Duke (Tupler) also pursued several objectives including:

1. refining the development of an automated ROCF scoring system;
2. directing a test and validation of the new scoring system using an existing experimental data set; and
3. preparing a manuscript documenting the test and validation results for submission to a neuropsychology journal.