Assessment of Executive Functioning using Virtual Reality: Virtual Environment Grocery Store

T.D. Parsons, A.A. Rizzo, J. Brennan, M. Bittman, E. Zelinski

***Abstract*— Longitudinal studies indicate that declines in cognition increase with advancing old age. Assessment of subtle losses in early stages of decline has been an elusive goal. While standard neuropsychological measures have adequate predictive value, their ecological validity may diminish predictions about real world functioning. Virtual environments are now being developed and tested with a focus on component cognitive processes. The increased ecological validity of neurocognitive batteries using virtual environments may aid differential diagnosis. We developed a Virtual Environment Grocery Store that involves a number of brief, shopping-type errands that must be completed in a real environment following certain rules that require problem solving. The Virtual Environment Grocery Store runs on an open-source NeuroVR virtual environment platform that includes an Editor and a Player that provide an interactive rendering system based on OpenGL. The NeuroVR Editor makes use of Blender and an integrated suite of three dimensional creation tools. Subjects navigate and interact within the Virtual Environment Grocery Store using the NeuroVR Player. While we have completed the development stage of this project, we are only beginning the data collection. We believe that this virtual environment will allow older adults to be evaluated in an environment that simulates the real world, not a contrived testing environment.

I. Introduction

LONGITUDINAL declines in neurocognition increase with advancing old age [1]. Neurocognitive declines are a predictor of functional loss in everyday abilities, such as financial management, shopping and cooking [2]. Proper assessment of neurocognitive declines (and their impact upon activities of daily living) is critical to reducing the costs of caring for elderly individuals and to improving the quality of their lives. Achieving this goal has been elusive. An area that may move us closer to this goal is study of executive functioning. Executive cognitive control declines with age and may be a major explanatory source of why older adults experience changes in multiple neurocognitive abilities. An additional factor is the dissociation between neuropsychological test performance and everyday behavior competencies in older adults. We argue that focusing on executive function in a more ecologically valid environment will move us closer to determining the possibility of reversing cognitive decline.

Over the past thirty years, various hypotheses have been identified to explain why memory, speed of processing, and language abilities decline with age. Current theories are based on findings of age declines in cognitive control tasks in which interference between competing responses (e.g. Stroop task: rapidly reading the color of the ink in which a word is printed and ignoring the word itself—e.g. BLUE, YELLOW) , a lag between occurrence of an item in a continuous series and having identify it (e.g. after a lag of 1 (1-back) vs. a lag of 2 (2-back), prospective memory (e.g. remembering to press a key when a blue box is shown on a computer screen), dual tasking: perform two tasks simultaneously (remembering a short list of words while pressing a response key to a signal), and monitoring of learning (self-testing of memorized material and rating the likelihood of remembering it later) occur [3]

These hypotheses and subsequent theories related to why memory, speed of processing, and language abilities decline with age reflect the effect of impaired goal maintenance functions that require executive cognitive control—the ability to plan, monitor, activate, switch, and to control competing responses where habits or cues are not sufficient to determine the best response, activation regulating functions to persist so that goals are attained [3], [4]. These functions are related to the integrity of the dorsolateral prefrontal cortex [4]. Further, the research suggests that functioning is impaired in the frontal lobes with age, and has been supported by neuroimaging studies of brain activation [3]. Executive cognitive control declines with age and may be a major explanatory source of why older adults experience changes in multiple cognitive abilities.

Executive function is assumed to represent a high level ability independent of other types of cognition, as it has been observed to underlie performance in a number of other functions, including problem solving and memory [4]. For example, memory deficits are not only due to inability to lay down memory traces; performance can be affected by other problems such as retrieval deficits, which may be due to lack of application of control processes to enhance recall. Importantly, level of executive function has recently been shown to be associated with functional ability: Performance on a

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T. D. Parsons is with the University of Southern California. School of Gerontology and Institute for Creative Technologies. 13274 Fiji Way, Marina del Rey, CA. 90292-4019. E-mail: tparsons@usc.edu; (v) 310.574.1632; (Fax) 310.301.5009.

A. A. Rizzo is with the University of Southern California. School of Gerontology and Institute for Creative Technologies. Marina del Rey, CA. 90292-4019. E-mail: arizzo@usc.edu.

J. Brennan is with the University of Southern California Institute for Creative Technologies. Marina del Rey, CA. 90292-4019. E-mail: Brennan@ict.usc.edu.

M. Bittman is with the University of Southern California Institute for Creative Technologies. Marina del Rey, CA. 90292-4019. E-mail: Bittman@ usc.edu.

T. M. Silva is with the University of Southern California Institute for Creative Technologies. Marina del Rey, CA. 90292-4019. E-mail: Silva@ict.usc.edu.

E. Zelinski is with the University of Southern California. School of Gerontology. Los Angeles, CA. E-mail: zelinski@usc.edu.

clinical test of executive control function (the Executive Interview; EXIT) was a predictor of self reports designed to assess the ability of elderly adults to complete instrumental activities of daily living [5]. Three-year declines in EXIT scores were associated with declines in functional status and were shown to mediate the relationship between memory decline and decline in functional ability [6], that is, executive function change was independent of memory decline.

A. Assessment of executive abilities

We are developing a psychometrically sound measure of executive abilities in everyday function. Most of the traditional neuropsychological tasks used to assess supervisory abilities were developed to localize brain damage as frontal relative to that of other regions. These tasks have also been used to test hypotheses that older adults have frontal deficits as an explanation for the cognitive changes associated with age. Many studies show that older adults perform more poorly on these tasks compared to those sensitive to other kinds of brain damage [3]. However, a serious problem with many traditional executive function tests like the Wisconsin Card Sort is that they are not repeatable because of substantial practice effects and cannot be used to assess training outcomes because of low test-retest reliability [7].

Beyond the issue of localization of brain damage, there are dissociations between neuropsychological test performance and everyday behavior competencies in older adults. Despite deficits on tasks associated with executive function, midlife adults showed no impairments [8], [9] in The Multiple Errands Test [10], a test of execution of everyday behaviors in a real shopping mall. The Multiple Errands Test evaluates how subjects complete a series of errands requiring organizing and planning in a real shopping mall. Activities in the Multiple Errands Test include following rules about entering particular shops, making purchases to meet a specified budget, and remembering to meet someone at a predetermined time without additional cues.

It is possible that older adults have everyday functioning deficits, but these may be too subtle to be measured with the Multiple Errands Test [11], which was developed as to assess actual behavioral functioning in frontal patients. The neuropsychological tasks most closely associated with frontal lobe deficits, therefore do not appear to fully reflect the range of performance on executive abilities in the everyday activities of older adults [12]. This has led to the proposal that that application of the principles of ecological validity is critical to the assessment of executive function [13]. Other assessments of behavioral competence in older adults, such as instrumental activities of daily living scales, which are more ecologically valid, may be good predictors of ability to remain independent, but they measure impairment rather than a range of ability. They are not specifically designed to assess impairment in activities of daily living relevant to executive function, and deficits may be attributable to multiple sources including visual impairments. We are currently developing an assessment that reflects a range of difficulty and has ecological relevance [13] by using a virtual reality platform.

B. Virtual Reality: applied tasks with laboratory control

Virtual reality (VR) is as an advanced computer interface that allows humans to become immersed within a computer-generated simulation. Potential VR use in assessment and rehabilitation of human cognitive processes is becoming recognized as technology advances. Since virtual environments (VEs) allow for precise presentation and control of dynamic perceptual stimuli (visual, auditory, olfactory, gustatory, ambulatory, and haptic conditions), they can provide ecologically valid assessments that combine the veridical control and rigor of laboratory measures with a verisimilitude that reflects real life situations. Additionally, the enhanced computation power allows for a range of the accurate recording of neurobehavioral responses in a perceptual environmental that systematically presents complex stimuli. Such simulation technology appears to be distinctively suited for the development of ecologically valid environments, in which three-dimensional objects are presented in a consistent and precise manner. As a result, subjects are able to manipulate three dimensional objects in a virtual world that proffers a range of potential task demands.

Virtual reality applications that focus on component cognitive processes, including attention processes [14], spatial abilities [15], memory [16], and executive functions [17], are now being developed and tested. The increased ecological validity of neurocognitive batteries that include assessment using virtual scenarios may aid differential diagnosis and treatment planning. Within a VE, it is possible to systematically present cognitive tasks targeting neuropsychological performance beyond what are currently available using traditional methods. Reliability of neuropsychological assessment can be enhanced in VEs by better control of the perceptual environment, more consistent stimulus presentation, and more precise and accurate scoring. Virtual Environments may also improve the validity of neurocognitive measurements via the increased quantification of discrete behavioral responses, allowing for the identification of more specific cognitive domains. Virtual environments could allow for neurocognition to be tested in situations that are more ecologically valid. Participants can be evaluated in an environment that simulates the real world, not a contrived testing environment.

Simulation of real world environments increases the ecological validity of the assessment task while maintaining control of manipulations that can affect performance [18]. Even though subjects are quite aware that virtual reality (VR) is just that, they willingly “play along” as though the environments are real [18]. Further, it has been argued that reality is experiential, not based on the external environment, and that immersive virtual reality tasks may produce subjective engagement that is equivalent to engagement in the real world [19].

Virtual reality has been used in a number of training and assessment situations and has been shown to have concurrent validity with neuropsychological measures. In one study, adolescents completing attention tasks over eight training sessions in a VR environment showed more performance improvement than those in a standard-computer trained group [20]. A study that evaluated fMRI activation during navigation and performance of tasks such as turning lights on or off, looking into all of the closets, and categorizing and counting the items in the closet of a virtual apartment found increases in frontal activation co-occurred with increasing task demands, with the closet task producing the largest blood oxygenation level dependent (BOLD) effects [21]. This suggested that the VR task produced activation in the targeted region of interest. In a demonstration of a VR adaptation of the Multiple Errands Task, [22] found that young adults with executive deficits completed fewer tasks than age matched controls, just as they did in the real version of the task. In this adaptation, however, no additional conditions were used to increase task demands.

We aim to systematically vary the information load (which affects goal maintenance) in an advanced VR version of the Multiple Errands Task by using multiple adaptive trials in the assessment procedure. This will be accomplished by creating a pool of “multiple task assignments”, empirically determining their baseline difficulty, and then adding conditions in the environment that will affect baseline task difficulty by manipulating the density of items on shelves, the similarity of packaging, and the intensity and types of realistic irrelevant distractions (e.g. loudness/type of muzak in the background and loudspeaker announcements). The range of difficulties will be used to make the task sufficiently complex that floor or ceiling effects will not be a problem.

II. METHODS

A. Project Progression

Whilst we have completed development of the virtual environment (see below), we have not yet run subjects through the scenario. Herein we describe the development of a virtual reality-based grocery store scenario and summarize the planned research design.

B. Inclusion and exclusion criteria

Strict exclusion criteria will be enforced to minimize possible confounding effects of comorbid factors known to adversely impact cognition, including psychiatric conditions (e.g., mental retardation, psychotic disorders, diagnosed learning disabilities, attention deficit hyperactivity disorder, and bipolar disorders, as well as substance-related disorders within 2 years of evaluation) and neurologic conditions (e.g., seizure disorders, closed head injuries with loss of consciousness greater than 15 minutes, and neoplastic diseases).

C. Apparatus

To assess executive ability, we developed a Virtual Environment Grocery Store (VEGS) that builds upon the multiple-errands test (MET) [23]. The VEGS, a 3D virtual grocery store environment, was designed to run on a Pentium 4 notebook computer with 1 GB RAM and a 128-MB DirectX 9 compatible graphics card.

This measure involves a number of brief, shopping-type errands that must be completed in a real environment following certain rules that require problem solving [10]. Activities in the VEGS are designed to parallel the MET.

The VEGS runs on open-source NeuroVR VE platform that includes an Editor and a Player that provide an interactive rendering system based on OpenGL. The NeuroVR Editor makes use of Blender and an integrated suite of three dimensional creation tools (see Figure 1).

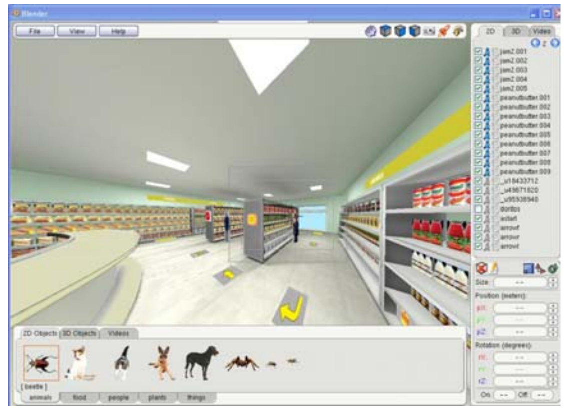

Fig. 1. NeuroVR Editor makes use of Blender and an integrated suite of three dimensional creation tools.

Subjects navigate and interact within the VEGS using the NeuroVR Player. Our prototype currently puts the subject in a non-immersive modality, in which the VE is displayed using a desktop monitor. The user interacts with the VE using the keyboard arrows and a mouse to make selections (see Figure 2). Tasks include:

- navigating through a virtual grocery store by following specified routes though the aisles
- finding and selecting items needed to prepare simple meals, such as making a peanut butter and jelly sandwich
- pricing and selecting other items so that no more than a budgeted amount is spent
- performing a prospective memory task when a certain individual is encountered.

Fig. 2. An aisle in the Virtual Environment Grocery Store.

Further, the difficulty of tasks assigned is increased over trials by adding distractions:

- increasing the number of items to store shelves
- adding background music
- increasing its loudness.

D. Procedure

Experimental sessions will take place over a half hour period. After informed consent is obtained, basic demographic information and computer experience and usage activities will be recorded. Participants will complete a neuropsychological battery administered under standard conditions, then complete the simulator sickness questionnaire, which includes a pre-VR exposure symptom checklist. Next, all participants will be administered the VEGS as part of a larger neuropsychological test battery.

The following traditional neuropsychological measures will be used: 1) Hopkins Verbal Learning Test—Revised (HVLT-R); 2) Brief Visuospatial Memory Test—Revised (BVMT-R); 3) Controlled Oral Word Association Test (FAS); 4) Semantic Fluency (Animals); 5) Digit Symbol Coding; 6) Digit Span (Forward and Backward) from the Wechsler Adult Intelligence Scale, Third Edition (WAIS-III); 7) Trail Making Test Parts A and B (TMT); 8) Stroop Color and Word Test; and 9) Wechsler Test of Adult Reading (WTAR).

III. DISCUSSION

Our goal is to conduct an initial pilot study to validate the VEGS through the use of a standard paper and pencil neuropsychological battery for the assessment of healthy participants. We believe that this will provide a first step in the development of this tool. Many more steps are necessary to continue the process of test development and to fully establish the VEGS as a measure that contributes to existing assessment procedures for the diagnosis of neurocognitive decline.

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