Virtual Reality and Driving: The Road to Better Assessment for Cognitively Impaired Populations

Abstract

Individuals with cognitive impairments can be faced with difficulties that may challenge their ability to drive an automobile, and this impairment is often very disruptive to vocational, social, and domestic activities. Rehabilitation specialists are often given the task of determining capacity to drive. However, traditional assessment methods are fraught with various limitations, including dependence on subjective interpretation of behaviors, nonstandardized procedures, and few ecologically valid measures. A virtual reality-based driving-assessment system (VR-DAS) offers the opportunity to overcome many of the limitations of current methodologies. Specifically, a VR-DAS permits the development of relevant driving scenarios that can provide objective and quantifiable measures of driving behaviors, allowing for increasing standardization and consistency of protocols. VR-DAS also allows for the creation of realistic and interactive driving scenarios at varying levels of challenge and complexity. When coupled with the immersive features offered through a head-mounted display (HMD), the VR-DAS may allow drivers to experience the sense of real-life driving, resulting in behavior and responsiveness that may be more predictive of actual driving ability. To examine these potential benefits and the validity of a VR-DAS, a collaborative study is presently being conducted, comparing VR-DAS performance and actual behind-the-wheeler performance in adults with acquired brain injury (such as traumatic brain injury and stroke).

I Introduction

In today’s society, the ability to drive an automobile is an integral component of maintaining an independent living status. Subsequently, the loss of this privilege can have a detrimental impact on various aspects of daily living, including work, leisure, and domestic activities. For individuals with neurological disorders, such as traumatic brain injury (TBI) and stroke, the ability to maintain their driving privileges remains important. However, these individuals are frequently faced with a sequelae of impairments that can lessen their ability to drive an automobile. Specifically, cognitive dysfunction including decreased attention and visual perceptual skills, slowed information-processing speed, and executive dysfunction have been demonstrated to significantly impair driving skills and ability (Galski, Bruno, & Ehle, 1992; Gouverner et al., 1989; Haikonen et al., 1998; Hopewell & Van Zomeren, 1990). As a result, the evaluation of driving capacity following neurological compromise requires careful analysis of the individual’s cognitive, physical, and behavioral abilities.
Rehabilitation specialists (such as neuropsychologists and occupational therapists) commonly face the task of determining driving competence following neurological impairment. However, given the lack of standardized guidelines, much variability exists in currently available protocols. Indeed, a critical review of common driving-assessment methodologies reveals various limitations, including the lack of ecologically valid measures, non-standardized protocols, and subjective interpretation of performance (Fox, Bowden, & Smith, 1998; Galski, Ehle, & Bruno, 1990). The application of virtual reality (VR) technology to driving assessment after acquired brain injury (ABI) offers an innovative approach to addressing many of these limitations.

To date, VR has been successfully integrated into several aspects of medicine, including the treatment of phobias (Rothbaum et al., 1995), training of surgeons (Satava, 1996), and education of patients (Medical Readiness Trainer Team, 2000). In addition, a number of researchers have integrated VR into neuropsychological assessment and rehabilitation of cognitive functions (Hoffman, Doctor, Patterson, Carrougher, & Furness, 2000; Rizzo, 1994; Rizzo & Buckwalter, 1997) and for training instrumental activities of daily living, such as the use of public transportation (Brown, Kerr, & Bayon, 1998) and meal preparation (Christiansen et al., 1998). The results of these studies have illustrated some of the benefits of integrating VR technology and neuropsychology in the development of new assessment and rehabilitation tools.

One area of rehabilitation that could significantly benefit from the unique features offered through the use of VR is the assessment of driving ability among individuals with cognitive impairment. At present, only a handful of studies have been conducted exploring the use of VR for driving assessment (Hirsekorn & Taylar, 1998; Liu, Miyazaki, & Watson, 1999; Wald, Liu, & Reil, et al., 2000). As such, many questions remain regarding the reliability and validity of VR as a tool for determining the driving capacity among individuals with cognitive impairment.

In this article we will (i) provide a brief background of the traditional protocols available for the assessment of driving capacity in cognitively impaired individuals, (ii) describe the benefits provided by VR for addressing the limitations of current driving-assessment protocols, and (iii) provide a brief description of a current collaborative study developing a VR driving system that is designed to assess the cognitive demands of driving.

2 Traditional Driving-Assessment Protocols

A review of driving-assessment protocols reveals that neuropsychological tests, behind-the-wheel evaluations, and performance on simulator vehicles are the most commonly used methods for the evaluation of driving capacity following cognitive impairment (Galski, Bruno, & Ehle, 1993; Kewman, Seigerman, Kinter, & Chu, 1985; Korner-Bitensky, Sofer, Gelinas, & Mazer, 1998; Lings, 1991; Schiff, Arnone, & Cross, 1994). But, due to the lack of standardized guidelines, much variability exists in the use of these protocols. A more critical review reveals that these protocols are fraught with numerous limitations. For example, although the use of neuropsychological tests has been widely researched (Croft & Jones, 1987; Gouvier et al., 1989; Korner-Bitensky et al., 1998; Korteling & Kaptein, 1996) and has resulted in the identification of specific cognitive domains that are deemed important to driving (such as, visual perception, and attention), the ecological validity of these measures remains questionable. Specifically, neuropsychological tests do not provide sufficient detail to predict what kind of everyday driving problems an individual may experience, nor do they yield information regarding the nature or frequency of the problems (Wilson, 1993).

Other researchers have used computerized tasks, such as the Useful Field of Vision (Ball & Owsley, 1993; Ball, Owsley, Sloane, Roenker, & Bruni, 1993) and the Elemental Driving Simulator (Gianutsos, 1994) to assess specific skills believed to be important in driving. However, due to their simplified graphics and lack of interaction, questions regarding the generalizability of these measures have been raised. In addition, similar to neuropsychological tests, these tasks commonly assess individual cognitive skills and do not allow accurate
evaluation of complex behaviors that incorporate multiple cognitive skills (such as driving). Traditional driving simulators (like the Doron Driving Simulator) have also been used to address the limitations seen in neuropsychological tests and computerized tasks (Galski et al., 1993; Quigley & DeLisa, 1983). However, to date, there is little evidence to indicate that traditional driving simulators do anything more than assess an individual’s basic ability to manipulate an automobile (Lings, 1991). Researchers have correctly reported that, although traditional driving simulators present dynamic stimuli, they lack user interaction, thereby reducing the overall validity of this measure (Liu et al., 1999). Additionally, given the high price of traditional driving simulators, criticism regarding the cost-effectiveness of these devices has been raised.

One common theme seen throughout the literature examining driving assessment of cognitively impaired populations is the use of behind-the-wheel (BTW) evaluation as the ultimate criterion of driving ability. As a result, the BTW evaluation is commonly regarded as the “gold standard” in driving assessment (Brooke, Questad, Patterson, & Valois, 1992; Fox et al., 1998). Unfortunately, this is done at a considerable expense, as BTW evaluations are commonly based on non-standardized, subjective observations of on-road driving behavior. Specifically, BTW evaluations occur on instructor/evaluator-selected routes, ranging anywhere from an empty parking lot to busy highways. Not surprisingly, for safety issues, effort is made to minimize the probability of challenging driving situations during the BTW evaluation. For instance, night driving, congested traffic, or emergency situations are often not included in these evaluations. Yet, it may be that these types of driving situations may be the most informative for the determination of driving competence and most predictive of how persons with cognitive impairment will perform in real-life driving situations. The lack of standardization in BTW measures or protocols also results in variability and inconsistency between evaluation sites.

Finally, it is notable that most research examining driving ability has been conducted with minimal incorporation of theoretical models of driving behavior. In fact, models of driving performance can help experi-menters design meaningful studies, allow the inclusion of associated performance measures, and develop more-reliable methods for assessment of driving skills. For example, one commonly cited model which has been minimally tested is Michon’s Model of Driving Behavior (Michon, 1985). This three-level hierarchical model suggests that cognitive processing is fundamental for driving. The levels of the model are (i) strategic, which involves tasks prior to commencing driving (such as route planning, determining conditions for driving), (ii) tactical, which involves executing maneuvers during actual driving (speed management, passing other vehicles), and (iii) operational, which involves more basic driving skills (steering wheel, left-right discrimination). Although traditional driving assessment protocols have typically not provided the opportunity for the evaluation of behaviors at all three levels, the identification and categorization of skills relevant to driving could be better determined through the inclusion of this model.

3 What are the benefits of VR in Driving Assessment?

Overall, VR offers a potential mechanism for addressing many of the limitations seen in current driving-assessment methods (see table 1 for summary), and offers the potential to revolutionize current assessment standards in several ways. Specifically, in its application to driving assessment, VR offers several benefits, each of which are explained in the following subsections.

3.1 Development of Ecologically-Valid Driving Assessment Measures

Unlike traditional protocols, VR simulation offers a medium for delivering real-life driving scenarios for the assessment of driving capacity in several distinctive ways. For example, VR allows the creation of an unlimited number of interactive and modifiable driving environments, which can allow clinicians to assess the impact of cognitive impairment in real-life driving environments, provide varying levels of difficulty based on an individual’s needs and abilities, and allow the safe
assessment of driving skills within more-challenging driving scenarios. Additionally, the real-life driving environments created by VR, combined with its interactive features and immediate performance feedback, allow an individual to “experience” the driving scenario, maximizing the potential for transfer of learning to an individual’s real environment. Indeed, in VR it is possible that drivers may experience a sense of “immersion” and perform with the same level of risk-taking as when driving in the real world (Nash, Edwards, Thompson, & Barfield, 2000).

### 3.2 Objective Assessment of Driving Behaviors

Through its capacity to allow clinicians to measure all behavioral responses while allowing control and consistency in both stimulus delivery and performance recording, VR can provide a mechanism for objectively quantifying driving skills. This can contribute to an improved understanding of the underlying cognitive demands of driving. In fact, prior work using VR driving simulators for evaluating specific driving-related tasks serves as an example of how specific skills can be identified and categorized (Levine & Mourtant, 1998; Mourtant & Ge, 1999). From this, development of models of driving behavior based on objective measures is possible. For example, a visual search model of driving behavior would predict that often drivers are complacent in monitoring the forward scene, but yet, when an “unexpected” event occurs, their visual search process becomes very active in seeking a safe path for their vehicle. VR environments can easily include such events, such as the vehicle directly in front of the driver suddenly braking, a package falling off a truck directly in front of the driver, or another vehicle running a stop sign. Such scenarios can be generated consistently for all subjects, and the recording of responses specifically designed for these individual scenarios can be achieved with VR simulation.

<table>
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<th>Current Driving Assessment Protocols</th>
<th>Limitations</th>
<th>How VR Addresses Limitations</th>
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| Neuropsychological tests            | · Assess only individualized, not complex behaviors and skills  
                                      · Questionable ecological validity | · Allow assessment of “complex” behaviors, such as driving  
                                      · Allows assessment of driving skills in “real-life” situations |
| Computerized tasks                  | · Simplified graphics  
                                      · Limited user interaction | · Interactive, detailed, “real-life” graphics  
                                      · Maximum user interaction |
| Driving simulators                  | · Variability in level of interaction  
                                      · Financially inaccessible | · Immersive effect allows higher level of interaction  
                                      · Increased advances in technology allow for a financially affordable system |
| Behind-the-wheel evaluations        | · Based on subjective observations  
                                      · Limited driving scenarios due to safety | · Allows for objective recording of all driving measures and behaviors  
                                      · Easily modifiable environment allows assessment under various conditions  
                                      · Controlled environment allows for safe evaluation of driving in complex and challenging situations |
|                                     | · Nonstandardized procedures | · Allows for standardized assessment |
3.3 Consistency Across Evaluators

Given the standardized, objective measures provided through VR, consistency and standardization of driving evaluations can be obtained. As previously noted, a current limitation among driving assessment protocols is the lack of guidelines or standards for determining driving competence. This variability, combined with the varying state-by-state differences in laws and regulations, can result in conflicting definitions of driver capacity. As such, the addition of a VR-based driving measure can help to institute standards for driving assessment and make current protocols more systematic. The result would be a more reliable and valid measure of driving capacity that would be beneficial to clinicians, patients, and other drivers.

3.4 Cost Effectiveness

Because VR technology is currently available for standard PC computers, this methodology, in comparison to other methods (traditional driving simulators and trained BTW evaluators), has the potential to minimize the current cost of driving evaluations, which are commonly an out-of-pocket expense for TBI and stroke survivors (Rosenthal, Griffith, Kreutzer, & Pentland, 1999). In today’s rapidly changing technical environments, most simulators will become outdated in a few years. Because VR simulators are low-cost as compared with traditional driving simulations, they may be updated at less cost.

3.5 Improved retraining protocols

The modifiable nature of VR also allows clinicians to tailor the evaluation to an individual’s specific needs, thus allowing for differences in stimulus presentation and response requirements based on specific cognitive impairments. For example, individuals who demonstrate difficulties in divided attention may be trained in a VR environment through continuous exposure to driving tasks that require attending to more than one stimulus or situation (for example, driving while tuning the radio station). Of particular clinical interest is the fact that VR can allow for immediate feedback and analysis of driving performance. Currently, errors made on the road during BTW evaluations are commonly reviewed and discussed at the end of the evaluation, at which point, the patient may have forgotten the incident or have difficulty recalling the details of the incident. In VR, on-road errors can be immediately addressed, and both feedback and detailed review of the error can be completed on site.

An important and related skill for driver retraining is increasing the patient’s awareness of driving capabilities. Not surprisingly, given the impact on social reintegration that driving can have, and the fact that many aspects of driving are considered to be a function of rote learning, individuals are often reluctant to voluntarily relinquish their driving privileges. As such, a VR driving simulator can serve as a safe method for examining an individual’s ability under challenging situations and for increasing awareness of real-life driving capacities. Work supporting this application has already been initiated (Wachtel & Schold-Davis, 2000).

3.6 Increased Accessibility to Evaluations.

The rapid development of VR technology has decreased the financial expense needed to acquire a VR system. As a result, VR has become a practical and accessible methodology, which can be acquired by those individuals who are most commonly faced with the task of assessing driving ability (independent clinicians and small rehabilitation centers). It is highly likely that the costs of acquiring and using VR driving simulators will continue to decrease.

Given the numerous benefits offered through the use of VR, it is not surprising that VR-based driving-assessment protocols have been created, and in some cases made commercially available (Hirsekorn & Taylar, 1998). However, further research is needed to validate this new tool; to date, these studies are sparse.

To this end, a collaborative project between Kessler Medical Rehabilitation Research and Education Corporation (KMRREC) and the Virtual Environments Laboratory at Northeastern University has been initiated to examine the efficacy of a VR-based driving-assessment
system (VR-DAS) in persons with acquired brain injury. The project described involves a neuropsychological approach to the assessment of driving, particularly for the evaluation of the cognitive demands of driving among clinical populations (traumatic brain injury and stroke). As such, the VR environments will be tailored to target specific cognitive skills and abilities identified as relevant to driving. To date, studies applying VR-driving-simulator programs to clinical populations are few (and many have focused on driving phobia), but none have directly compared these driving simulators to current available methodologies of driving assessment. The described project directly addresses these limitations by directly comparing a VR driving system to the current “gold standard” in driving assessment, the BTW evaluation, and by including individuals with cognitive impairment resulting from traumatic brain injury or stroke.

4 Development of the VR-DAS

4.1 Preliminary Study

The current study is based on prior research involving the Neurocognitive Driving Test (NDT) (Schultheis & Chute, 1999). Through the use of PowerLaboratory software and a modified steering wheel and foot pedals, on a Mac-based platform, the NDT allowed the presentation of varying driving-related tasks. Specifically, measures of latency and errors were recorded during a video movie presentation of complex driving scenarios. Unlike traditional driving simulators, the NDT allowed for a minimal level of user interaction. Initial studies comparing NDT performance between healthy controls and adults with traumatic brain injury indicated a significant correlation between measures of NDT performance and pass/fail performance on a comprehensive hospital-based driving evaluation. Based on these findings, it was hypothesized that, given the higher level of user interaction, increased opportunity for measuring more-specific driving behaviors (lane position, speed management), and mechanism for presenting alternate levels of difficulty, a VR system based on these findings would increase the efficacy of this tool.

4.2 The VR-DAS

For the development of the VR-DAS, consideration into the demands of driving as well as the needs of the clinical population were closely examined. Given the fact that driving can be regarded as a highly vision-based task, the field of view (FOV) provided by the simulator was an important factor for the creation of a realistic driving environment. Driving simulators with a large FOV and a high-resolution scene provide drivers with the opportunity to acquire visual information in a similar manner to that encountered when driving in the real world. However, VR simulators with large (180 deg. or greater) FOVs are expensive to acquire and operate. For the proposed study, we will use a helmet-mounted display (HMD), coupled with an unobtrusive head-tracking system. HMDs are available with a 60 deg. FOV and, when used with head tracking, will allow a driver to experience a 360 deg. FOV (60 deg. at a time).

Given the clinical population included in the current study and the expected cognitive difficulties (such as decreased attention and difficulties when concentrating), an HMD-based VR system was specifically selected to minimize opportunities for distraction from the virtual driving environment. Additionally, it was hypothesized that the HMD, coupled with environments designed specifically to give drivers a feeling of immersion, would result in increasing the subjects’ belief that they were driving in the real world. In the past, the use of HMDs with VR driving simulators has been limited. This may have been due to their relatively low resolution (640 × 480 pixels) and/or high cost. Recently, HMDs with higher resolution (1024 × 768 pixels) have become available and enable the presentation of high-quality driving scenes. We expect the use of these displays to contribute to an effective VR simulator experience for cognitively impaired drivers.

4.3 Ongoing Study

For this initial study, the VR-DAS will be composed of three VR driving scenarios, each with a duration of approximately fifteen to twenty minutes. The first scenario was selected to allow direct comparison
between driving performance on a typical behind-the-wheel evaluation and driving performance in the VR-DAS. Specifically, a VR analog of the current route employed by the Kessler Driving Program will be created. This route encompasses driving through a residential section, several city intersections, and a brief open highway route. As subjects are driving, measures of driving speed, lane position, and maneuvering errors (such as not stopping, or following too close) will be recorded using a standardized checklist.

The additional two driving scenarios were selected to allow examination of challenging factors on driving ability. Specifically, one scenario will include the additional factor of nighttime driving. This will be achieved by using the same VR analog of the Kessler route, with the additional nighttime graphics. The third scenario will include the additional factor defined as “complex” driving. Specifically, this scenario will also use the VR analog of the Kessler route, but will have additional programming to include more-challenging driving situations in specific locations. For example, additional traffic will be added to the city intersections and pedestrians crossing will be added to the residential section. In addition, emergency situations (such as a fire engine suddenly pulling out) will be added to the route. By maintaining the VR analog of the Kessler route consistent throughout the two additional VR driving scenarios, we plan to independently examine how the two additional factors affect driving performance. Measures of driving performance (described earlier) will be recorded for both the nighttime driving and “complex” VR routes.

The first proposed study is designed to examine the efficacy of a VR-DAS and will include two groups of subjects: subjects with a history of acquired brain injury (ABI) resulting from either a traumatic brain injury or stroke and matched healthy control subjects. First, to evaluate the concurrent validity of a VR-DAS, driving performance of ABI subjects on the traditional hospital-based BTW evaluation will be compared to driving performance of ABI subjects on the VR-DAS. Specifically, all ABI subjects will complete (i) the Kessler Driver Evaluation, which consists of a pre-driver “off-road” evaluation (comprising a brief battery of motor and cognitive tests) and a BTW evaluation and (ii) the first VR-DAS driving scenario (the VR analog of the Kessler route). For both driving protocols, driving performance will be measured using a performance checklist developed at the Kessler Driving Program. Comparison of specific driving measures (speed, lane positioning) and overall driving performance (pass versus fail evaluation) will be examined. Furthermore, to elucidate the potential effects of demographic and medical factors that may impede or facilitate driving performance within a VR environment for this clinical population (that is, ABI), medical, social, and neuropsychological measures will be obtained.

The second objective of the study will involve the evaluation of the effects of the addition of complex and challenging driving factors (nighttime and complex driving) to driving performance within a VR environment. To examine this, performance of matched healthy control subjects on the VR-DAS (scenarios 1 through 3) will be compared to the VR-DAS performance of ABI subjects. Currently, the study is in the development phase, whereby programming and identification of specific driving situations and driving performance measures are being defined. Data collection is anticipated to commence within the coming year.

Conclusions

In recent years, desktop computers and their associated graphics components have experienced dramatic increases in processor speed and significant decreases in cost. As a result, they can now be used to construct cost-effective VR driving simulators, which can serve as tools for delivering ecologically valid driving situations while simultaneously obtaining objective measures of driving behavior. Likewise, the major advances in the resolution and ergonomics of HMDs now make them cost-effective components, which can further help promote a feeling of immersion and greater sense of “real driving.” Combined, VR technology delivered through an HMD system has the potential to revolutionize current methodology in the assessment of driving capacity following cognitive impairment and offers numerous
benefits to both clinicians and patients. Although much work is still needed to further determine the reliability and validity of a VR-based driving-assessment simulator, it is foreseeable that, in the future, these simulators may become the tool of choice for driver assessment, education, and training.

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