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RESEARCH PAPER

Using virtual reality driving simulators in persons with spinal cord injury: three screen display versus head mounted display

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Purpose: **Virtual reality (VR) is a relatively new technology that is currently utilized in a wide variety of settings to test and train individuals in specialized skills. This study examines methods for improving driver retraining protocols for persons with spinal cord injury (SCI).** ***Method:*** **We compared a VR driving simulator, under two different display conditions, a head mounted display (HMD) and a three screen display (TSD) to identify the best method for retraining driving skills following SCI.** ***Results:*** **Although there was minimal evidence for driving performance difficulties in the HMD condition relative to the TSD condition (e.g. greater number of times for being off course and longer stopping latencies for the HMD condition), rates of simulator sickness did not differ between display conditions.** ***Conclusions:*** **Taken together, findings suggest that both the HMD and the TSD are reasonable simulator options for driver retraining in SCI.**

Keywords: Spinal cord injury (SCI), virtual reality, head mounted display, screen display, driving simulator

Implications for Rehabilitation

- Virtual reality (VR) may be a useful tool for improving driver retraining for persons with spinal cord injury (SCI).
- Both head mounted display (HMD) and three screen display (TSD) virtual reality systems are reasonable simulator options for driver retraining in SCI.

The ability to drive influences various aspects of both daily living and level of independence. After traumatic spinal cord injury (SCI), the ability to drive has significant impact on the ability to participate in work and recreational activities [1] and influences perceived overall quality of life [2,3]. Further, individuals with SCI who drive independently are more likely to be employed [4]. Although independent driving after SCI is important, there is very little research examining driving rehabilitation in this population, with only one study examining virtual reality (VR) technology for driver retraining in SCI [5].

The concept and definition of VR has been subject to debate by scientists and clinicians over the years. VR has been very generally defined as "...a way for humans to visualize, manipulate, and interact with computers and extremely complex data [6]". From this baseline perspective, VR can be seen as an advanced form of Human-Computer interface [7] that allows the user to "interact" with computers and digital content in a more natural or sophisticated fashion relative to what is afforded by standard mouse and keyboard input devices. In some cases, with the aid of specialized VR display devices, users can become "immersed" *within* a computer generated simulated environment that changes in a natural/intuitive way with user interaction.

Recently, researchers have begun using VR as a tool for clinical rehabilitation [8,9]. VR has demonstrated utility in cognitive retraining in cerebral palsy [10], motor retraining in stroke [11], balance and control in vestibular disorders [12], balance and mobility in traumatic brain injury [13], and community training skills in acquired brain injury [14]. In regards to SCI rehabilitation, VR has primarily been used for physical rehabilitation including upper arm movement [15], balance [16], and exercise [17]. While VR technology is gaining favor as a tool for clinical rehabilitation, there are only a handful of studies that have utilized VR as a potential tool for driving rehabilitation [18]. Specifically, there is support

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for the use of the VR driving simulator in individuals with brain injury, with studies demonstrating a significant positive relationship between VR driving and behind the wheel performance [19–21]. In addition, individuals with acquired brain injuries showed improvements in driving performance with repeated exposure to the simulator [22], and driving simulators can discriminate between individuals with and without brain injuries [23]. The single study in SCI that examined a VR driving simulator examined the relationship between traditional foot controls and the specialized hand controls used by individuals with SCI [5].

Although current research is limited, the success of VR training for a wide variety of rehabilitation applications suggests that VR simulation may be a viable option for driving retraining after SCI. However, to maximize efficacy of VR as a training tool in rehabilitation, it is important to minimize health risks of VR simulation, such as simulator sickness [9,24]. Previous research has suggested that simulator sickness rates range from 20% to 60% in VR simulations [25]. These high rates suggest that the issue of simulator sickness must be addressed and minimized before relying on VR as a viable and practical rehabilitation tool. Further, there is some evidence to suggest that HMD simulation may carry higher rates of simulator sickness [26], suggesting that other types of simulators (e.g. TSDs) may be preferable to HMDs.

The current project was designed to examine the utility of two different VR display conditions in an SCI population. This study examines the use of a TSD simulator versus a HMD. Specifically, we compared and contrasted these two conditions on: performance (adverse events and stopping behavior; See Table I) and simulator sickness.

Method

A total of 54 individuals with traumatic SCI participated in a driving evaluation study using a virtual reality simulator. After removing one HMD participant due to technical problems with the simulator and one TSD participant due to voluntary withdrawal, 26 participants were randomized to the HMD condition and 26 participants to the TSD condition. Participants ranged from 18 to 65 years of age (M = 37.9; SD = 13.3) and 87% were male; 51.9% were Caucasian, 25.9% African American, 14.8% Hispanic, and 7.4% indicated other ethnicity. Average time since injury was 8.94 years (SD = 11.0); 29.6% were attributed to violence (e.g. gunshot wound), 18.5% to motor vehicle accidents, 16.7% to falls, 16.7% to sports injuries, and 18.5% from "other" causes. SCI diagnosis indicated 74.1% were paraplegic and 25.9% were tetraplegic; 66.7% sustained complete injuries and 29.6% reported incomplete injuries. Participants were recruited from the Kessler Driving Program, the Northern New Jersey SCI model system, and advertisements in SCI consumer newsletters. Inclusion criteria permitted individuals both with and without any experience with hand controls for driving. All data was collected in accordance with the ethical standards of local Institutional Review Boards; participants provided written informed consent prior to enrollment in the study.

Table I. Driving performance variables evaluated by the simulator.

Variable name	How quantified
Number of "On Road" Collisions	Number of collisions with either stationary objects (parked cars, buildings, barriers in construction zone, guardrails on highway, street signs, etc.) or moving objects or people (vehicles, the ball in the residential challenge, kids in the crosswalk in the school zone, etc.)
Number of "Off Road" collisions	The number of resets indicates the number of occasions where the study coordinator had to reset the VR program when the driver went completely out of the track on the driving path.
Longest stop duration	The program indicates the duration for each time the participant applied brakes in response to stopping in front of a stop sign. The longest stop duration was the longest amount of time that the participant was stopped in front of the stop sign.
Total times brakes were applied	This reflects the number of times that each participant applied the brakes prior to coming to a complete stop before the stop sign.

HMT and TSD did not differ on any of the demographic variables: age, t (50) =0.22, p =0.16; gender, n = 23 males and n = 3 females for both groups; or ethnicity, χ^2 =0.36, p = 0.95. Further, groups did not differ on variables related to SCI including: time since SCI, t (50), = 0.43, p = 0.91; diagnosis, χ^2 = 2.56, p = 0.11; etiology, χ^2 = 5.7, p = 0.22; or severity, χ^2 = 0.37, p = 0.54.

Virtual Reality Driving Simulator: Hardware. This study utilized a specially designed virtual reality simulator that incorporated hand controls for acceleration and deceleration, and adaptive equipment for steering (e.g. spinner knob, tri-pin). The modified steering column was attached to a specially designed table that could be optimized to accommodate differences in the height clearance for different models of wheelchairs. This hardware was combined with either the TSD screens or a HMD, and a personal computer to create the simulator.

Virtual Reality Driving Simulator: TSD. The TSD was comprised of three, 30-inch Dell LCD Monitors (Model W3000). Each monitor offers a native resolution of 1280 × 768, a widescreen image aspect ratio of 16:9, and image contrast of 350:1. Monitors were positioned to provide a seamless three-screen visual display (see Figure 1).

Figure 1. This picture shows the 3-screen visual display utilized in this study.

Virtual Reality Driving Simulator: HMD. Digital Media Works (DMW), http://web2.dmw.ca/, modified the eMagin Z800 3D Visor, for use in this study. This system utilizes two OLED SVGA microdisplays (800 × 600), as well as on-board 3D frame sequential video processing, an integrated X, Y & Z-axis head-tracker, and attached stereo sound. This HMD offers a viewing equivalent of a 105 inch diagonal movie screened viewed at a distance of 12 feet, offering a brilliant, sharp and flicker-free motion image to its user. Specifically, resolution for images is 1.44 megapixels per display (full color >16.7 million pixels), includes 24-bit color, and a high contrast ration of > 200.1. The visor is lightweight and ergonomic, weighing less than 8 ounces.

Virtual Reality Driving Simulator: Software. DMW also designed four different driving zones (residential, school, commercial and highway) within a closed-loop environment (see Figure 2 for an example screen shot of the residential zone). Participants in both the TSD and HMD went through two separate fixed routes within each of the four driving zones; the software provided verbal directions to ensure that drivers stayed on route. We collected information related to driving quality including adverse events and stopping behavior (see Table I for variable descriptions). Although each route that a participant completes is fixed, the program can be modified by the examiner to vary both the order of zone presentation and the difficulty level within each zone. Specifically, the program allows for changes in the number of static vehicles (e.g. cars parked in driveways or at the side of the road) or dynamic vehicles (the amount of traffic on the road), and includes eight challenges (two in each zone) that can be enabled (e.g. turned on or off) separately. Challenges include a ball that suddenly rolls out into the middle of a street with a child (who is about to follow the ball into the street) masked from view by a parked car (residential zone) and a car that runs a red light and crosses in front of the participant's car (commercial zone). The combination of start zone selection and options for each zone (e.g. clutter, traffic, and challenges) results in the ability to develop unique simulations for either research or clinical purposes. The software collects information related to driving quality including speed, lane position, use of turn signals, and any adverse events (e.g. collisions, running off the road). Finally, the program contains two training environments that are simplified versions of the four zones used in the closed loop environment. Specifically, these zones contain short stretches of roadway with grassy areas to the side; the exclude architectural elements or dynamic/static vehicles in these training zones. The training zones merely provide the user with a brief exposure to simulator functions (including the hand controls) prior to the administration of a full simulation session. The software is compatible with windows-based browsers.

Simulator Sickness Questionnaire: This questionnaire includes 27 items covering 16 symptoms commonly experienced by users of VR systems to assess simulator sickness. Items were rated on the following likert scale: none, slight, moderate and severe. This questionnaire was administered prior and subsequent to VR exposure.

Data analysis: The driving simulation program generated three output files (raw, log, and fid files) for every test run. Information from these files was used, post process, to calculate and generate variables to evaluate driving performance during simulation. Data was analyzed using Matlab software (MathWorks, Inc).

The log file registered an event: every time a driver collides with the other cars or objects in the VR, and when the study coordinator had to reset the VR program due to the driver being completely outside of the specified driving track. These event logs were used to calculate the number of "on road" and "off road" collisions for each of the school, commercial, and residential zone to evaluate the performance of participant based on the level of difficulty in the VR environment presented by the various driving zones on the route.

The raw files recorded information regarding the vehicle position in the virtual environment, its location relative to other objects, its speed (in mph), and the active target (a stop sign or traffic signal etc.). The information from raw file combined with the log file was used to analyze stopping at the stop signs. A program was coded to calculate the duration for which a driver stops at a stop sign and the distance from the stop sign. In general, the driver applied brakes multiple times in response to stopping in front of a stop sign resulting in multiple stops. The longest stop was used to evaluate the driver's performance in response to a stop sign.

Results

Driving performance

A series of t tests indicated that there were several group differences on driving performance variables (see Table II). Specifically, individuals in the HMD condition had more "off road" collisions (which represents the total number of times a driver is completely off the specified driving path) in the residential zone than individuals in the TSD condition. In addition, individuals in the HMD condition stopped for a longer duration at all three stop signs than individuals in the TSD condition.

Figure 2. This screenshot shows the car approaching an intersection within the Residential Zone.

Table II. Means/corrected means and standard deviations/standard errors for driving performance variables.

Driving performance variable	HMD M(SD)	TSD M(SD)
Number of "On Road" collisions		
Community	0.23 (0.87)	0.25 (0.61)
Residential	0.82 (1.01)	0.50 (0.66)
School	0.14 (0.47)	0 (0)
Number of "Off Road" collisions		
Community	0.09 (0.29)	0.08 (0.28)
Residential	0.59(0.91)***	0 (0)***
School	0 (0)	0 (0)
Longest stop duration		
Stop sign 1	5.35 (5.53)*	2.05 (1.98)*
Stop sign 2	2.67 (2.75)*	0.93 (1.37)*
Stop sign 3	2.81 (2.58)*	1.11 (1.22)*
Total times brakes were applied		
Stop sign 1	1.35 (0.49)	1.54 (0.59)
Stop sign 2	1.35 (0.81)	1.21 (0.83)
Stop sign 3	1.30 (0.73)	1.13 (0.54)

Note. Two participants that were identified as outliers were excluded from longest stop. Duration analyses.
*p < 0.05.
**p < 0.01.
***p < 0.001.

Simulator sickness

Five participants (19.2%) in the HMD condition and 2 participants (7.7%) in the TSD experienced acute simulator sickness during the protocol requiring termination of participation; results of a Fisher's exact test did not indicate significant group differences (p = 0.23). Results also did not indicate group differences on simulator sickness at any time point: pre-simulator, t (51) = -0.65, p = 0.29; or after simulator session, t (51) = 0.37, p = 0.52. There were no significant group differences in reported simulator sickness prior and subsequent to VR exposure, t (20) =–1.27, p = 0.22 for HMD; t (23) = –1.02, p = 0.32 for TSD.

Discussion

Findings from this study suggest that both a HMD and a TSD appear to be reasonable options for virtual reality driving simulations in users with SCI. Specifically, although there were some statistically significant differences in driving performance, with individuals in the HMD condition exhibiting longer stopping durations (suggesting more hesitancy or head movement), and more "off road" collisions in the residential setting, these differences were very small and not likely to indicate clinical or functional differences in driving performance. In addition, simulator sickness rates did not significantly differ between conditions, and were consistent with rates reported in other studies [24,27]. Further, these rates were consistent with "best" simulators [25,27].

Although either simulator appears to be a viable option for use in SCI, there are a few reasons why the TSD may be slightly better than the HMD. First, fewer participants experienced simulator sickness in the TSD condition (although not significantly less than the HMD). Further, the TSD was associated with fewer "off road" collisions than the HMD (comprised of cars parked on the right side of the road and included sharper and more number of turns) suggesting that TSD provides better VR interface in more challenging virtual environments. Finally, shorter stopping durations for the TSD may also suggest more comfort with the TSD VR interface, relative to the HMD condition; however, it is equally plausible that the longer stopping durations in the HMD reflect the need for participants to turn their head to view crossing traffic in the HMD condition, but not in the TSD condition, making the HMD a more "realistic" VR experience. In addition, the stop sign analysis indicated that the participants applied brakes multiple times in response to stopping in front of a stop sign both in the HMD and TSD condition. The multiple stops included one or more stops of duration less than 1 second and one longer stop (several seconds). These shorter stops would mean that the driver was applying brake gradually to stop but did not intend to stop yet or that the driver's response to stop at stop sign was just a momentary stopping (if there is only one stop and that is less than 1 second in duration).

While findings suggest that VR simulators are appropriate for use in SCI, it is important to recognize some of the limitations of the current study. First, this study did not include a behind the wheel test condition, so more research is needed to determine the generalizability of VR findings to behind the wheel driving rehabilitation. Further, although rates of simulator sickness were consistent with other studies, it is possible that a larger sample is needed to detect effects between groups on simulator sickness. It is also important to recognize that driving rehabilitation in SCI offers unique challenges. For example, research highlights the importance of seating stability (i.e. the influence of inertial forces related to braking and turning) for individuals with SCI when driving [28–30]. Furthermore, driving modifications (such as collision avoidance warnings, cruise control, vision enhancement systems, vehicle control locations, etc.) may differentially impact driving ability, performance, and safety in individuals with SCI [31]. Future work must consider these issues when addressing the driving rehabilitation needs of the SCI community.

In conclusion, our findings suggest that the VR simulators are appropriate for use in individuals with SCI. While more research is needed to understand the relationship between simulator performance and driving rehabilitation in SCI, VR appears to be viable option for driving retraining. The accessibility of VR can serve to enhance current driver retraining protocols, potentially minimizing the number of training sessions (and subsequent out -of-pocket expense) sessions for patients.

Declaration of Interest

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