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Head-Mounted Displays for Clinical Virtual Reality Applications: Pitfalls in Understanding User Behavior while Using Technology

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ABSTRACT

The use of virtual environments with head-mounted displays (HMDs) offers unique assets to the evaluation and therapy of clinical populations. However, research examining the effects of this technology on clinical populations is sparse. Understanding how wearers interact with the HMD is vital. Discomfort leads to altered use of the HMD that could confound performance measures; the very measures which might be used as tools for clinical decision making. The current study is a post-hoc analysis of the relationship between HMD use and HMD comfort. The analysis was conducted to examine contributing factors for a high incidence of simulator sickness observed in an HMD-based driving simulator. Pearson correlation analysis was used to evaluate objective and subjective measures of HMD performance and self-reported user comfort ratings. The results indicated weak correlations between these variables, indicating the complexity of quantifying user discomfort and HMD performance. Comparison of two case studies detailing user behavior in the virtual environment demonstrates that selected variables may not capture how individuals use the HMD. The validity and usefulness of the HMD-based virtual environments must be understood to fully reap the benefits of virtual reality (VR) in rehabilitation medicine.

INTRODUCTION

With the advent of faster and affordable hardware and accessories, virtual reality (VR) systems are being explored for a wider range of applications beyond flight simulation and three-dimensional (3D) gaming. One area where this trend can be seen is in medicine. Recent applications of virtual reality in medicine have included surgical[1] and dental training[2] and clinical performance assessment.[3–5] Findings indicated that supplemental VR training improved skills and shortened surgical procedure time, making VR a good training tool. VR has also expanded into broader areas including the use of the technology for treatment and for clinical decision-making. For example, VR has been used in conjunction with exposure therapy for fear or anxiety conditioning, such as fear of heights and fear of driving.[6–8] VR has also been successfully applied for distraction of pain during various medical procedures.[9]

In rehabilitation medicine, VR can offer several unique assets to both assessment and treatment of physical, cognitive and behavioral disabilities.[10]

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Research findings from a handful of studies underscore the potential value of this technology.[11–13] One evolving and promising rehabilitation application of VR is the use of VR-based driving simulation for the assessment and retraining of driving capacity following neurological compromise. Traditional driving assessment methods have been fraught with limitations such as lack of generalization and ecological validity, subjectivity or bias potential, and a limited ability to test individuals in complex, challenging, and possibly hazardous driving situations.[14] On the other hand, VR driving simulations present safe but challenging driving situations, in a graduated and individualized manner, while providing clinicians with objective and repeatable measures of driving behavior.

VR applications can require different degrees of immersion in the environment in order to achieve the desired effects, and therefore use different combinations of hardware and software to deliver these virtual environments (VEs). Complex visual environments are not always needed; in some cases, other inputs may be more beneficial. For example, Keshner and Kenyon reported that the study of postural control using immersive technology may be better served using a motion platform to include vestibular and proprioceptive inputs in addition to visual inputs.[15] In contrast, retraining arm and finger manipulation activities might require a higher visual display resolution to relay fine finger control or addition of haptic feedback to the fingers, while a motion platform for vestibular input is less important.[12]

A higher degree of visual immersion may be beneficial to compensate for the effects of cognitively-related difficulties. For example, among individuals who have sustained a traumatic brain injury, it is not uncommon to see attentional difficulties,[16] including visual distraction.[17] VR-related interventions that help individuals "shut out" the real world or focus attention on the task at hand may lead to more useful and successful clinical tools. HMDs can accomplish this more effectively than an external monitor, and for this reason, HMDs provide a unique feature that should be considered for some rehabilitation VR applications.

From a technical perspective, the immersion is achieved using a hardware tracking device mounted on an HMD. The tracking device couples the user's head movement with the virtual environment by detecting changes in head orientation, and this information is used to correctly update the visual scene presented to the user (within the HMD). The end result allows the user to choose what they look at by simply moving their head. This provides a greater level of autonomous interaction with the VE, and allows the user to scan the virtual world over 360 degrees.

HMDs: clinical applications and concerns

While the popularity of VR technology is growing, reports of usability problems have marred its luster. Side effects such as simulator sickness are commonly estimated at 20%, with "worse" simulators reaching a 60% occurrence rate.[18] Given these findings among the healthy population, some researchers have raised concerns about how to appropriately apply this technology to clinical populations.[19]

One usability concern is comfort of the HMD. Despite its popularity, HMD use is sometimes avoided in clinical applications because of side effects such as simulator sickness and visual fatigue. However, the exact incidence of these side effects in clinical populations, including those with brain injury, has not been well-established. Studies to date using HMD-VR systems for rehabilitation in clinical populations are still limited and the efficacy of the method continues to be evaluated.[20] Researchers have acknowledged that additional exploration of HMD delivery is needed,[21–23] especially if VR will be used with clinical populations and if clinical decisions will be based on the measured VR outputs.

The HMD use and comfort analysis presented here is based on an HMD-based virtual reality driving simulator, although the challenges and concerns presented apply to all virtual reality applications that use HMD devices to deliver visual information. The Virtual Reality–Driver Rehabilitation System (VR-DRS)[14] allows individuals to safely practice driving in a variety of realistic residential and commercial driving environments with common challenges such as pedestrian crossings and speeding vehicles, while providing repeatable and objective measures of driving behavior. It was designed for use with clinical populations (e.g., individuals with stroke, brain injury) and includes driving scenarios designed to challenge the various demands (e.g., cognitive) of driving. To date studies with the VR-DRS have revealed reasonably favorable user-feedback ratings.[24]

With the incidence of reported side effects associated with HMD use, it is tempting to eschew HMDs in favor of large screen projection displays. This trend has begun. The majority of driving simulators are screen-based systems ranging from a basic PC monitor to multiple high resolution projectors and screens to provide a wide field of view.

Of those using an HMD with clinical populations, none investigate the comfort and usability of the HMD, the side effects of HMD delivery, or how HMD use may impact user performance. For example, Wald et al.[25] evaluated the DriVR simulator (Imago Systems, Inc.) to predict driving performance for individuals with brain injury. The authors reported that the HMD-based system had a noticeable lag between head-tracking and visual updates in the HMD, although the effects of this lag were not explored.[26]

HMD technology has been steadily advancing in the last five years to reduce the technical issues associated with side effects such as simulation sickness. Reductions in cost have made HMDs more accessible. The technology should be reassessed, rather than abandoned, in order to retain the positive aspects of immersion that HMDs alone can provide.

Assessing usability and comfort of HMDs

Assessing usability and comfort of the hardware and software aspects of VR environments is difficult due to the wide range of technologies and products. If HMDs are to be used in clinical populations, side effects and usability concerns must be addressed, although few clear recommendations exist on how to evaluate usability and comfort. It thereby falls to the developer and end users (i.e., clinicians and researchers) to validate that the product is appropriate for its intended uses.

Previous studies have used both subjective and objective measures to evaluate VR system usability including the degree of immersion or "presence."[27] Subjective measures include user feedback (questionnaires, rating scales and interviews), while objective measures include physical and physiological parameters such as head position, heart rate, body sway, and skin conductance.[18,27] Additional objective measures can include any data reported from the simulator itself; such as head turn angle.

Only one study has addressed HMD comfort in healthy individuals. Bangay and Preston[28] developed a roller coaster virtual environment to explore factors that influence the characteristic of immersion in an environment. Measured head movement (using a motion tracker and HMD) was the only variable to show correlation with self-reported comfort level of the HMD (using a Likert scale questionnaire). Individuals who turned their heads more reported the HMD to be "very comfortable." One conclusion of the study was that effectiveness of the immersion is significantly influenced by the comfort of the peripherals, including the HMD.

Objectives of the study

Given the dearth of information available regarding HMD use with clinical populations, the current study focused on potential issues with adults with acquired brain injury. Specifically, the study investigated whether HMD comfort factors were related to HMD use during a VR driving simulation by examining the relationship between objective measures of HMD use and subjective measures of user comfort. As in the Bangay and Preston study, it was anticipated that a significant relationship would be seen between HMD comfort and use.[28]

METHODS

Participants

Data from 20 individuals with acquired brain injury (ABI) and 10 healthy controls (HC) were analyzed. This group is a subset of a larger population ($n = 54$) and included only those who did not suffer simulator sickness and who completed the entire VR driving route. The ABI group included individuals who experienced a moderate to severe traumatic brain injury ($n = 12$, or 60%) or a cerebrovascular accident (CVA) or stroke ($n = 8$, or 40%). Subjects were recruited through the Kessler Driving Evaluation Program (Saddle Brook and West Orange facilities) and via advertisements through the Brain Injury Association of New Jersey. The sample included 22 male and eight female participants. The average age was 41.6 years, average education was 15.2 years, and 83.3% of the sample was Caucasian ($n = 25$), 6.7% Hispanic ($n = 2$), 3.3% African American ($n = 1$), and 6.7% self-reported as "other" ($n = 2$). No significant difference in age, education or years of driving experience was observed between the two groups.

Apparatus

Virtual reality driving rehabilitation simulator (VR-DRS). The VR-DRS is composed of hardware and software elements (Fig. 1). The hardware includes a steering wheel and gas/brake foot pedals (Microsoft Sidewinder), and a head mounted display Proview™ XL50 Virtual Reality Display headset with 1024 × 768 resolution and 50° diagonal, 30° (V) × 40° (H) field of view, (Kaiser Electro-Optics, Inc.) with a motion track with 2-msec latency and 1° accuracy (Intersense I-Cube gyroscopic/geomagnetic sensor). The virtual environments were delivered using a desktop computer (Gateway

FIG. 1. Virtual Reality–Driver Rehabilitation System (VR-DRS).

multiprocessor 701-MHz Pentiums) with a video update rate of 60 frames per second.

The VR-DRS software was patterned after the actual driving route used for clinical driver evaluations conducted by the Kessler Institutes for Rehabilitation in New Jersey, and includes nine separate areas (e.g., residential, merging, commercial), each with several typical driving scenarios that individuals could encounter while performing daily activities (e.g., pedestrian crossing road, traffic). Total course drive time is 25–35 min.

One area of the VE was selected for this analysis because it relies heavily on head turning to traverse the route. It includes a challenging left turn onto a four-lane roadway (two lanes in each direction with no center turn lane), with oncoming vehicles crossing the intersection. This complex intersection that requires the subject to fully scan left and right in order to merge into new traffic patterns safely. An aerial view and approaching screen shot are show in Figures 2 and 3.

The VR-DRS generates four quantitative output variables that are sampled every 200 msec during simulation. No filtering is performed. These mea-

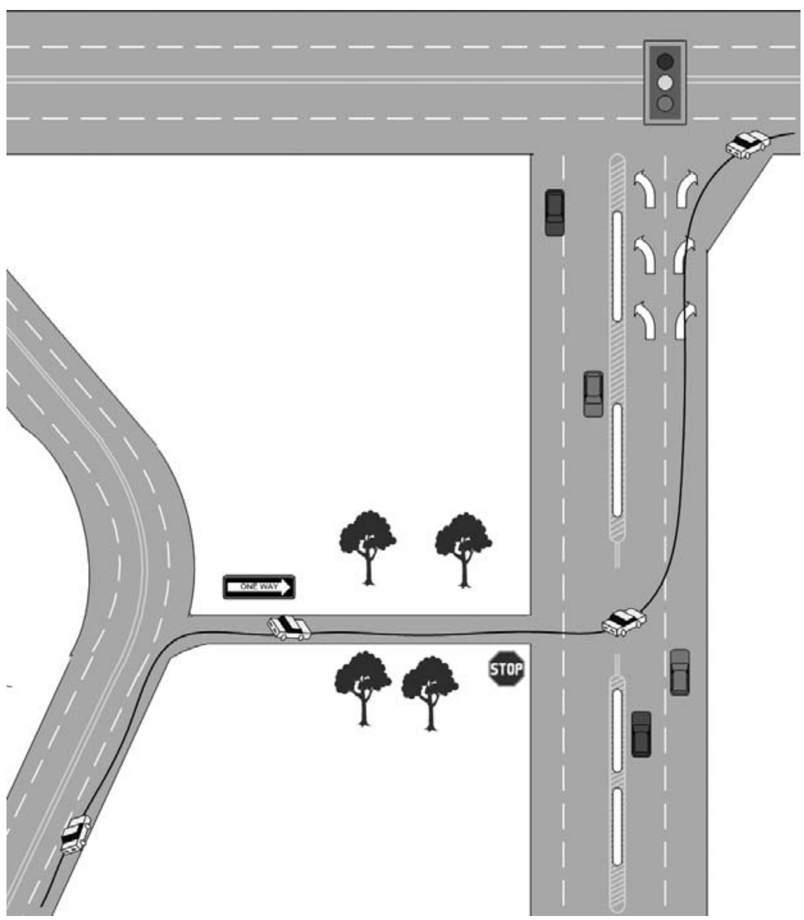

FIG. 2. Aerial view of the merging scenario, a short portion of the total drive route that has an uncontrolled left turn at a dangerous stop sign intersection, followed by an immediate right turn at a traffic signal. The car's path shown here is representative of the path driven by most participants.

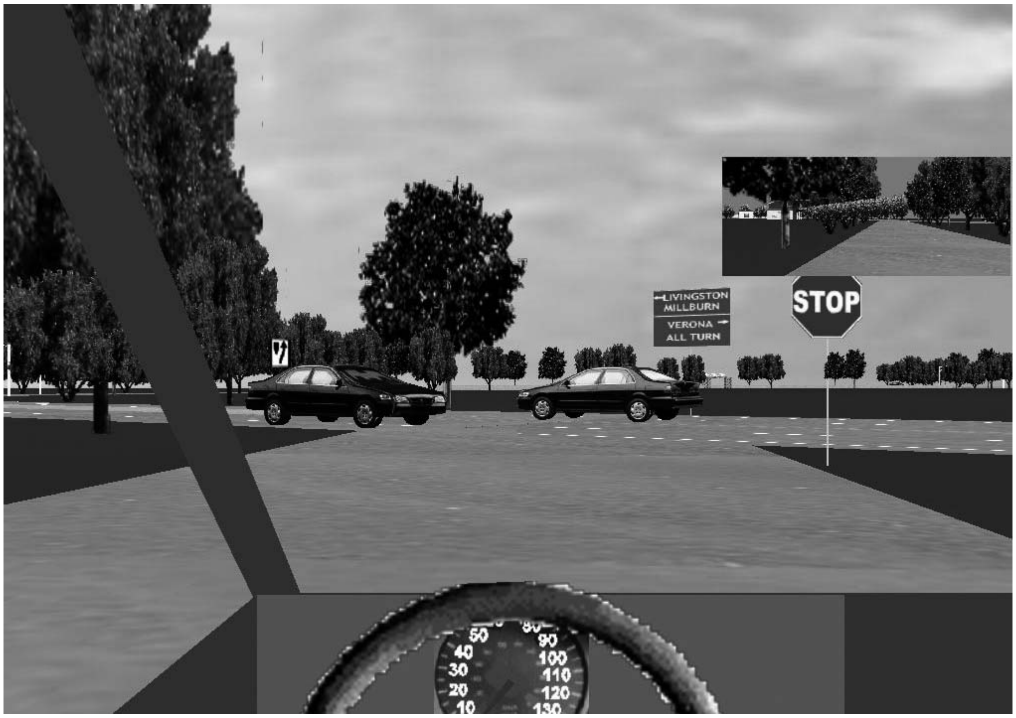

FIG. 3. A screen shot shows the car approaching the uncontrolled intersection. The participant is instructed to proceed to the stop sign and make a left turn. Side views (available from within the head-mounted display [HMD]) are not shown.

sures include speed (in miles per hour), deviation from lane center (in feet), distance to a stop sign or a traffic light (in feet), and head turn angle to the left or right (in degrees). Head turn angle was used as an objective measure of HMD use for this study. Two specific HMD performance measures were defined based on the premise that (1) increased use of the HMD would constitute a higher level of comfort using the device and that (2) the investigation should focus on driving scenarios where head turning/scanning the environment was a critical component. Therefore, HMD performance measures included (1) head turn scanning throughout the entire scenario and (2) head turn scanning before proceeding into the challenging uncontrolled intersection.

VR-DRS user feedback questionnaire. The VR-DRS User Feedback Questionnaire is an eight-item questionnaire to assess participant feedback on the mechanical aspects of the VR-DRS (e.g., steering wheel, foot pedals, HMD), features of the virtual environment (e.g., lane markings, traffic signs), and subjective comfort using the VR-DRS. This questionnaire does not separate types of discomfort (e.g., headache, eye strain, simulator sickness). For each item, participants assigned a numeric value from 1 to 9 (1 = strong disagreement; 9 = strong agreement). This generates an overall score (User Feedback Total Score) where higher scores indicate more favorable VR-DRS use.

Two output variables from this questionnaire were used as subjective measures of HMD comfort. These are the total score (representing general comfort using the entire VR system), and one item addressing comfort with the HMD specifically.

From these two instruments (simulator, questionnaire), two sets of output variables are defined: objective HMD Performance variables and subjective User feedback variables. These are summarized in Table 1.

Procedure

At the start of the test session, all participants completed an Institutional Review Board consent form and required HIPAA authorization forms. Prior to the driving trials, all participants practiced driving in the VR-DRS. This practice period allowed participants to familiarize themselves with the VR-DRS (e.g., steering wheel, foot pedals, HMD). Participants were instructed how to use the steering wheel and foot pedals and were provided specific driving directions (e.g., "stay in the right hand lane and maintain a speed of 35 mph"). Each of two practice trials

TABLE 1. OUTPUT VARIABLES FOR OBJECTIVE MEASURES OF HMD PERFORMANCE AND SUBJECTIVE SELF-REPORTED USER RATINGS

Output variable name	*Description*
HMD performance variables (objective)	
Max head turn left	Maximum angle that the subject's head is turned to the left throughout the scenario
Max head turn right	Maximum angle that the subject's head is turned to the right throughout the scenario
Head turn difference	Difference between the maximum left and maximum right head turn angles
Total summed head turn	Total head turn summed over entire scenario
Stop sign max head turn left	Maximum angle that the subject's head is turned to the left at the stop sign
Stop sign max head turn right	Maximum angle that the subject's head is turned to the right at the stop sign
Stop sign number of scans	Number of times the subject's head turned to the left and to the right at the stop sign
Self-reported user variables (subjective)	
VR-DRS total score	General comfort using the entire system
VR-DRS HMD score	Comfort with or difficulty using the HMD

HMD, head-mounted display; VR-DRS, Virtual Reality–Driver Rehabilitation System.

required participants to come to a full stop on three separate occasions, two on curved portions of the route and one on a straight portion of the route. Participants received a graded exposure to the system; the first practice trial was completed without using the HMD (a normal flat-screen computer monitor was used), while the second practice trial used the HMD. At the completion of both practice trials, all participants were administered the VR-DRS User Feedback Questionnaire. For this study, it is important to note that user feedback was solicited after the practice period and prior to the VR-DRS testing trial. Participants reporting no negative side effects of VR exposure continued to the testing trial.

Statistical analysis

Two-tailed Pearson correlation coefficients were used to evaluate the relationship between objective and subjective measures of comfort. Independent samples t-tests were used to compare objective and subjective measures between the clinical and healthy groups. For all analyses, a p value of <0.05 was considered statistically significant.

RESULTS

The purpose of this study was to examine the relationship between HMD use and comfort. To achieve this, Pearson correlations analysis were used to examine this at two levels. The first compared objective measures of HMD use (HMD Performance variables) to subjective measures of general VR user feedback (VR-DRS total score) and the second compared objective measures of HMD use to specific subjective measures of HMD comfort feedback (VR-DRS HMD score).

Several significant, although weak, correlations were found between the objective and subjective measures (Table 2). First, the further a subject scanned to the right at the challenging stop sign intersection, the less they report having difficulties using the VR-DRS overall (VR-DRS total score: r = 0.466, p = 0.009, n = 30), and with the HMD specifically (VR-DRS HMD score: r = 0.448, p = 0.013, n = 30). A significant correlation between the maximum left head turn and the total VR-DRS score was also observed (r = 0.385, p = 0.036, n = 30).

In addition, subjects who favored turning their head to one side more than the other reported having more difficulties using the HMD while driving the entire scenario (VR-DRS total score: r = 0.416, p = 0.22, n = 30). In other words, subjects who are not comfortable using the HMD did not scan across their visual space evenly; instead, they tend to look further to the left than to the right (or vice versa). Overall, subjects who scanned more fully to the left and right at critical points in the virtual environment reported greater comfort with the HMD

TABLE 2. RELATIONSHIP BETWEEN SUBJECTIVE AND OBJECTIVE MEASURES OF COMFORT IN CHALLENGING MERGE AREA, AND SPECIFICALLY AT THE UNCONTROLLED STOP SIGN INTERSECTION

	VR-DRS Total score r	*VR-DRS HMD score r*
Entire area		
Max left head turn	0.385*	0.130
Max right head turn	0.334	0.361
Head Turn Difference	0.043	0.416*
Stop sign intersection		
Max left head turn	0.343	0.188
Max right head turn	0.466**	0.448*
Number of scans	0.064	0.165

*$p < 0.05$, two-tailed.
**$p < 0.01$, two-tailed Pearson correlation analysis.
VR-DRS, Virtual Reality–Driver Rehabilitation System; HMD, head-mounted display.

(VR-DRS HMD score) and fewer difficulties using the system overall (VR-DRS HMD score).

A secondary post hoc analysis was undertaken to evaluate if similar findings would be seen throughout the entire VR-DRS driving route. The same analysis was repeated for the previous driving scenario and the two subsequent areas (residential and highway scenarios). Controlled and uncontrolled intersections were included. Overall, none of the objective variables was significantly correlated with the User Feedback HMD Score (VR-DRS HMD score; Table 3). Maximum right head turn and total head turn were significantly correlated with the User Feedback Total Score (VR-DRS total score; $r = 0.374$, $p = 0.042$, $n = 30$, and $r = 0.377$, $p = 0.040$, $n = 30$), respectively. Similar to the first analysis, the results shows a significant, although weak, correlation between objective and subjective measures.

Finally, the differences in both subjective and objective measures were compared between the clinical and healthy groups using t-tests. Results indicated no significant difference in any of the six objective HMD Use variables between the two groups. In addition, no significant difference in the two subjective measures of comfort between the two subject groups was found. Results are summarized in Table 4.

TABLE 3. RELATIONSHIP BETWEEN SUBJECTIVE AND OBJECTIVE MEASURES OF COMFORT IN EXTENDED DRIVE ROUTE

	VR-DRS Total score r	*VR-DRS HMD score r*
Extended route		
Max left head turn	0.350	0.108
Max right head turn	0.374*	0.292
Total summed head turn	0.377*	−0.214

*$p < 0.05$, two-tailed.
**$p < 0.01$, two-tailed Pearson correlation analysis.
VR-DRS, Virtual Reality–Driver Rehabilitation System; HMD, head-mounted display.

DISCUSSION

The study focused on issues related to HMD use with adults with acquired brain injury and investigated if subjective HMD comfort factors were related to objective measures of HMD use during a VR driving simulation, in order to measure and predict usability and comfort more objectively. The findings weakly support a positive relationship between subjective measures of comfort and objective HMD performance variables, where higher amounts of head turn are positively correlated with user reports of comfort with the equipment. No significant differences were observed between the

TABLE 4. GROUP DIFFERENCES BETWEEN HEALTHY CONTROLS AND INDIVIDUALS WITH ABI FOR THE SUBJECTIVE AND OBJECTIVE MEASURES

	t	*Significance*
Entire area		
Max left head turn	0.029	0.977
Max right head turn	0.339	0.737
Head turn difference	0.599	0.554
Stop sign intersection		
Max left head turn	−0.335	0.740
Max right head turn	0.938	0.356
Number of scans	0.000	1.000
VR-DRS total score	0.406	0.688
VR-DRS HMD score	−0.858	0.398

*$p < 0.05$, two-tailed.
ABI, acquired brain injury; VR-DRS, Virtual Reality–Driver Rehabilitation System; HMD, head-mounted display.

healthy control group and the ABI group for either the subjective or objective measures.

These results are similar to Bangay and Preston who reported that a correlation exists between head movement and user reported comfort where individuals "with the most head motion find the head mounted display to be very comfortable."[28] Participants in both studies reported approximately the same degree of comfort using the HMD: average comfort for the VR-DRS was 57.5%, and for the roller coaster was 62.5% (to compare, scores from each study were normalized from 0% to 100%).

While both studies compared aggregate and descriptive measures of head movement, the VR-DRS was an active experience that required the participant to look around and control their interaction with the simulation using hardware controls, while the roller coaster simulation was non-interactive and the participant could remain passive. Bangay and Preston reported that observed head turning was low, with mean head movement of 7.6°/sec over the ride versus our mean value of 12.6°/sec over the driving scenario. This difference is related to the demands placed on the participant, but gives no indication if the degree of head turning is actually a result of HMD comfort.

For this reason, we believe that understanding HMD comfort requires evaluating more than just aggregate measures like total scan angle or maximum and minimum head turn angles. The remainder of this discussion focuses on the information available when considering real-time head turning data rather than aggregates, and how these data can be used to evaluate comfort, and identify and avoid reported HMD usability problems.

Real-time head-turning behaviors

The weak link between the subjective and objective measures prompted us to explore raw head turn data from two participants (Fig. 4). The subject in Figure 4a reported being very comfortable using the HMD and the system overall. This individual slowed down appropriately while approaching the stop sign, looked right, inched forward, and fully scanned the environment left and right before entering the intersection. Figure 4b shows an individual who felt neutral about using the HMD and the system. This individual approached the intersection turning slightly to the left of his previous head turn angle (by 10 degrees) and appropriately came to a stop. Without looking either direction, the individual coasted into the intersection and then turned another 13 degrees to the left to scan for incoming traffic. Only then does he look slightly to the right after committing to enter the intersection. The first individual used the HMD to scan the environment more fully and the left-right pattern of scanning at the intersection is evident. Head turn range of motion (ROM) is computed as the sum of the maximum left and right head turn angles; the ROM for the first individual at the stop sign is 132° versus 17° for the second individual.

These plots allow insights that would be missed using descriptive statistics, or if head turning was investigated independently of speed and other objective data. Specific driving behaviors such as planning and execution to safely enter this challenging intersection can be evaluated. The first individual stopped at the stop sign for 7.2 sec, while the second individual stopped only 1 sec, which is insufficient to negotiate this intersection safely. While this individual had difficulty negotiating the intersection, we cannot conclude if discomfort with the equipment was the source of the problem.

However, these plots may reveal evidence of HMD usability problems that have been reported in the literature. An empirical study of usability issues associated with HMD-based simulations reveals that half of the concerns are associated with the HMD device itself[29]; commonly cited causes are HMD cable entanglement around the user or chair, HMD weight, incorrect HMD fit, and nausea associated with HMD use. Nichols reported individuals had a "general discomfort from wearing the HMD," and a "fear of getting tangled in the connecting cables."[18,30]

The HMD can shift as the individual turns his head, causing the zero degree (or "looking straight ahead") position to be lost. This may have occurred in Figure 4a. The baseline head turn angle for the straight portion of road before the intersection is slightly offset to the right (7 degrees). After the individual scans fully to the left and right at the stop sign, the baseline head turn angle changes by approximately 11 degrees to 3 degrees to the left. It is impossible to know if the individual is now looking in a different direction, or if the HMD shifted on his head. While overall behaviors and total scanning range of motion can still be evaluated, the accuracy of the actual reported head turn angle must now be questioned. Approximately 30% of the data files show a baseline shift in centerline HMD position of 5 or more degrees (to a maximum of 15°) before and after major head turning activities. Any resultant effect on our statistical analysis is not known.

The individual in Figure 4b reported less comfort than the first individual, and did not turn his head fully any time during the trial. Head turn range of motion (ROM) for this individual was 26° over the

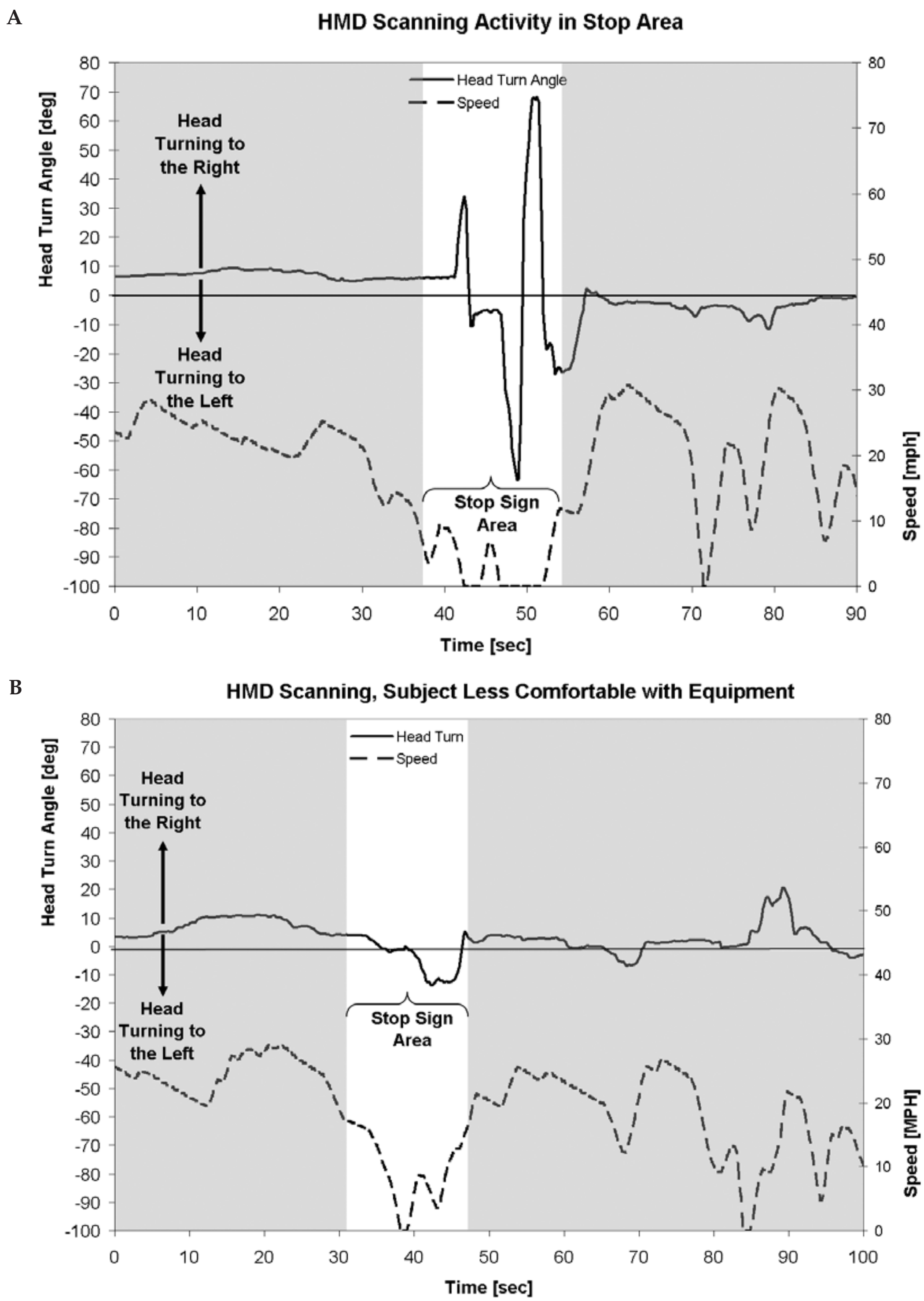

FIG. 4. Scanning activity in two individual participants. **(A)** Participant more comfortable with equipment. **(B)** individual less comfortable with equipment. In both plots, the top line shows head turn angle in degrees with positive values indicating head turns to the right, and negative values indicating head turns to the left. The bottom line shows car speed in miles per hour. Both plots are scaled identically. In this short area, participants drive the route shown in Figures 2 and 3. Participants are prompted to exit the first road and continue down the exit ramp to the stop sign, and then to make a left turn. This stopping area is indicated in each plot. The area finishes after a right turn at the stop light.

entire trial as compared to 132° for the first individual. This low usage of the HMD may be caused by the weight of the device, fit, or the fear of entanglement, which can decrease the tendency to turn the head. The VR-DRS questionnaire did not attempt to separate these effects. Over 30 subjects, the head turning ROM ranged from 3° to 127°, with an average ROM of 38° ± 46°. It is not known if HMD weight or cable restriction caused a reduced ROM in this study, although Simpson et al. report that these factors have caused difficulty in looking and moving around a road crossing virtual simulation.[31]

Is head turning related to comfort?

Although many individuals who reported discomfort or difficulty using the VR-DRS hardware did not turn their heads much during the driving simulation, this finding was not universally supported throughout the tested population. Several individuals who reported that the HMD made it somewhat difficult to drive actually turned their heads quite significantly. In fact, 60% of users with head-turning range of motion more than 100° reported difficulty with the HMD, with responses ranging from 5 to 9 (9 = "strongly agree") that "the HMD makes it difficult to drive in the simulator."

It is not clear if the HMD is causing difficulty or discomfort, or if the discomfort is causing decreased HMD use. These results suggest that factors other than comfort influence HMD head turning behaviors. Several conflicting factors may come into play, and the positive or negative effect of each on comfort and head turning is not fully known. First, Bangay and Preston report that increased comfort and increased HMD use are positively correlated.[28] Vection, or feelings of self motion, are important to the feeling of immersion but can also lead to simulation sickness. McCauley and Sharkey suggest that vection is required in order to induce simulator sickness.[32] Increased simulator sickness causes decreased HMD use as wearer limits head movements to reduce nausea.[33] Seagull and Gopher also found that helicopter pilots using HMDs while flying act to reduce disorientation caused by the HMD by reducing head movements or executing specific sequential head movements.[34] To overcome HMD limitations of reduced field of view and peripheral vision causing the disorientation, specific training was implemented to increase head movements. Head movement training improved flight performance significantly; Seagull and Gopher report that participants "seem to have acquired new scanning strategies" leading to "a substantial improvement in their ability to cope with the difficult task of flying with HMDs."[34]

Conflicting this is the natural tendency for normal users not to turn their heads in the HMD; thought to be based on our repeated exposure to TVs and large movie screens where "head turning is counterproductive."[35] Pierce also reports that users may not realize that they can turn their heads while wearing an HMD, and thus, do not do so. In this case, measures of smaller head turning do not necessarily signify discomfort.[35]

Other factors that affect head turning include physical factors. Reduced head turning may be caused by the weight of the HMD and drag associated with the attached cables. In addition, if the HMD is not securely fastened to the head and it shifts during use, as we suspect above, the wearer may purposely reduce head movements to prevent further shifts. This resulting change in head turn behavior may be completely unrelated to the actual comfort of the device.

Exploring the cause-and-effect relationship between HMD comfort and use is exacerbated by the lack of standardization of the hardware and of protocols. The dearth of controlled studies make truly understanding the effects of the hardware extremely challenging,[21,36] and specific explorations into HMD use are even less common. From our experience, too many factors can influence the wearer's comfort and the wearer's tendency to turn his head, and the relationship (if any) between the two could not be conclusively determined.

While immersive virtual environments are appealing for a number of medically related applications, the side effects of VR exposure may last hours after the exposure is complete.[37] A detailed review of ergonomics issues in virtual reality, including HMD-related issues, can be found in Nichols and Patel.[18]

CONCLUSION

Researchers and clinicians are recognizing the value of immersive environment but current trends are moving away from HMD use due to the problems observed. Many problems are caused simply because the virtual environments were not designed with attention to usability issues up front. While little work has been done to resolve usability and comfort concerns with HMD devices, a decision to avoid HMDs in favor of large screens should not be made lightly. HMDs can provide significant advantages over large screen systems that should not be discounted, especially in clinical populations. First, HMD-based system can be less expensive and require significantly less physical space; a common issue in the clinical setting. Second, HMDs can minimize the impact of cognitive disabilities and increase opportunity to engage the individual because external visual and auditory distractions can be reduced or eliminated. Third, HMD-based systems can be portable, allowing therapy or evaluation to occur in the office, at bedside, or even at home, broadly increasing delivery options. Therefore, we must consider how to manage the effects of HMDs in order to retain the benefits of the technology.

In analysis of use and comfort, there is no gold standard or protocol that has been defined for HMD and VR characterization or evaluation. Few objective methods exist to dynamically assess comfort and usability during the simulation itself, although detecting negative effects of simulations earlier rather than later should be a significant goal, especially for individuals with disabilities who may have higher susceptibility to side effects.[38] Although head turn has been proposed as a measure of comfort, our findings reveal that usability issues with the HMD itself likely affect the usefulness of the results, and that it may be impossible to isolate the effects of the HMD from the rest of the hardware platform, especially during post-hoc analysis.

Instead, appropriate attention to usability in the earlier design stages should lead to more standardized and validated measures of comfort and user acceptance and to fewer side effects from the technology. The incidence of side effects brings the obligation to explore the usability of HMDs, especially in clinical populations, if VR simulations are ultimately designed to be used as a clinical tool. The primary goal should be to validate the delivery method with actual users and then establish the validity of the resulting measurement tool. Then, the appropriateness and usefulness of such a tool will increase significantly.

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