Influence of peripheral and stereoscopic vision on driving performance in a power wheelchair simulator system

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***Abstract*—Training in a Virtual Environment simulating a power wheelchair, can enhance safety, cost-effectiveness, training quality, and can also be used for the assessment of potential future users. Power wheelchair simulators often lack correct physics simulation, do not support peripheral vision, or do not provide features required for assessment. Here we address these issues with a novel power wheelchair simulator and projection environment. Specifically we evaluate whether a narrow field of view, a wide field of view involving peripheral vision, and 3D stereoscopic projection influence the users' driving performance. We found that users' overall driving performance was significantly better with a wide field of view compared with a stereo or narrow view. The sense of presence was rated significantly higher by participants in the wide-view condition and participants also had a strong preference for this view. This suggests wide-view to be the most promising among the evaluated visualization conditions and should be considered in the development of virtual power wheelchair simulator systems.**

Keywords—human-computer interaction; assessment; mobility; virtual environments; projection environments

I. INTRODUCTION

Receiving a powered wheelchair (PWC) can be experienced as gaining a tremendous sense of freedom, yet, not every potential user is immediately able to make appropriate and safe use of it. Despite the increased number of PWC with an estimated 23,000 PWCs purchased every day, [1, p. 156] suggest that "the evaluation of user proficiency and the suitability of a given wheelchair is largely guesswork, and user training is limited to practice with a possibly unsuitable wheelchair". Harrison et al. [2] reported that a computer simulation, controlled by a joystick, could be a better training/assessment solution to avoid the danger of collisions in real situations. Niniss and Inoue [3] add that Virtual Environments (VE) can be considered as a useful tool to evaluate performance criteria, and Abellard et al. [4, p. 162] explain that exercising in a VE can "reduce previous constraints", "bring a solution to the safety problem", "diversify experiments", "evaluate driving capacities", and "quantify needs in terms of functionalities".

The two often mentioned reasons for developing such a system are to train targeted users how to drive a PWC, and to assess whether a person is suitable and eligible for a PWC. However, most of the current simulators (if not all) are not suitable as an assessment or training tool. Considering the current issues with existing simulators, here we aim to investigate factors that may influence user driving performance in PWC simulators and compare them, in particular the effects of various visualization conditions. With a PWC simulator developed for this purpose, this study compared users' driving performance across three different visualization conditions, namely 1) 2D monoscopic narrow field of view (narrow-FOV), 2) 2D monoscopic wide field of view (wide-FOV), and 3) 3D stereoscopic narrow FOV (stereo-FOV). Next to the driving performance, users' subjective experience of being part of the virtual environment (i.e. the sense of presence) and their preference was also evaluated.

II. BACKGROUND

A. *Filed of View*

A wide range of possible display technologies is used in VE. For example, there are head-mounted displays (HMD), arm-mounted displays, boom-mounted displays, workbench, fish-tank virtual reality, panoramic display, and CAVEs [5]. They all differ in their characteristics; of particular importance for this project are their immersive capabilities of stereoscopy (the display of binocular disparate images) and field of view (FOV). In general, the field of view is the degree of what human eyes can see. According to [6, 7], the maximum human FOV is about 200° horizontally and 100° vertically which also varies from one person to another [7]. In addition, the FOV is basically divided into three visions, see Fig 1: one is central vision where a person is looking straight ahead (about 5° viewing angle), the second is binocular vision, which is a result of the overlapping images of each eye (about 140°), and third is the peripheral vision that is around binocular vision, which does not allow for stereoscopic depth perception [6, 7].

Display FOV has two different FOV angles that must be taken into account [8]. The first is the angle subtended from the location of the observer's eyes to the screen edges (left and right), called the display field of view (DFOV). This angle depends on the user distance; the closer from the screen the larger the DFOV is. The second is the virtual camera angle, which is the angle subtended from the virtual camera to the sides of the image rendered on the screen, known as geometric field of view (GFOV), Fig 1.

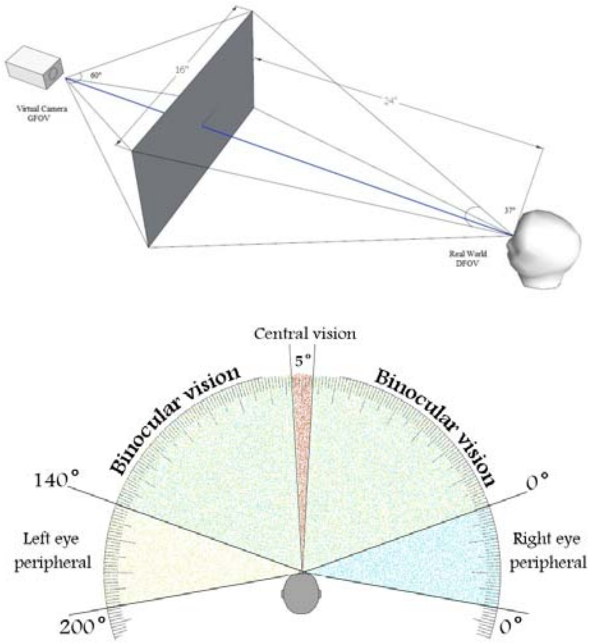

Figure 1. Human field of view on the right and the DFOV and GFOV on the left

B. *Power Wheelchair Simulators*

One of the earliest works using VE to assess the ability of PWC drivers was that of [9] in the early 90s. The aim was to provide a risk-free environment that would allow users to drive efficiently in order to evaluate their ability at PWC driving. A few years later, research conducted by [10] investigated the influence of a PWC driving simulator on disabled children's driving skills before and after training. Each subject was assigned a score out of 1000. The score was calculated as follows: Score = 1000 – (time spent in seconds + number of collisions). The inexperienced group showed a significant increase in their performance after training ($p < .005$).

In 2002, a project conducted by [2] used two non-immersive VE systems to assess and train PWC drivers. They focused on user manoeuvrability. In real life, participants' performances were measured pre and post training, as well as through VE. The system recorded the total time spent, distance travelled in each task, number of collisions, and number of manoeuvres. Although the results showed that tasks learned in the VR could be transferred to real life, manoeuvrability tasks were harder in the simulator than in real life, in particular driving in reverse [2] which could be linked with lack of peripheral vision and spatial location indicated by most of their participants.

A recent project, named miWe [11], concluded that PWC users' driving performance in VE was equivalent to their driving performance in real life. The main purpose of the miWe research was to compare participants' performance doing exactly the same tasks in the simulator and in real life. Their sense of presence was also measured by a standard questionnaire developed by Igroup Presence Questionnaire (IPQ) [12]. The video analysis showed that participants had some difficulties with sideways manoeuvring due to the lack of lateral vision in the virtual environment. The reason for this difficulty was attributed by [11] to the simulator's limited field of view of only 100° whereas the natural human field of view is more than 180°.

Browning et al. [13] were the first to use the CAVE environment for rehabilitation purposes, in 1996. The CAVE environment consisted of three walls (3 × 3 m) surrounding the user to display the projected image coming from three rear projections. This allowed the user to freely interact with the VE while being able to see their bodies. The authors suggested that this kind of environment was the most appropriate for PWC simulation. They also argued that the CAVE had the potential for sharing the environment with more than one person. There has been a body of research on (power) wheel chairs on motion platforms. A review of wheelchair simulation by [14] states that although adding a mobile platform to the simulator shows a higher performance, it also increases the complexity and cost of the simulator.

Despite a long history of research in PWC simulators, there is only one software product commercially available on the market, named WheelSim [4]. In this software, the task is to drive between two yellow lines in a given direction. Touching the yellow lines indicates a "minor mistake" and driving beyond the yellow lines is a "major mistake". Total time, the time added for minor and major mistakes, and the number of minor and major mistakes are recorded and combined to form a final score. Although the WheelSim software was designed 1) to help disabled persons to operate a PWC, 2) to improve road safety, and 3) to provide quantitative data that could be used for diagnostics and therapy purposes [15]. Our usability inspection with five evaluators revealed that WheelSim has a number of flaws that make it unsuitable for use as a training and assessment system. The most severe of these shortcomings was identified by the evaluators as the lack of an accurate physical simulation. In addition, the unknown size and driving speed of the PWC were identified to be problematic. Furthermore the joystick interaction in WheelSim is limited to only one speed (i.e. the PWC either drives or remains still) which is not an appropriate representation of the functionality of a real PWC joystick which is sensitive to the amount the joystick is moved and accelerates accordingly.

In summary, the review of the literature showed that PWC systems have been researched for training [10], [16], [17], and assessment purposes [2], [3], [4]. Commonly used performance criteria are the number of collisions either with objects or path boundaries and time spent for completion [2], [3], [9], [10], [15], [16]. Other studies also recorded user trajectories [3] and graphically represented them, and two studies calculated scores based on this data [10, 15]. The common problem is however that most of the simulator systems are rather simple, lack of peripheral vision, and do not provide a realistic experience, e.g., use incorrect physics simulation as the results of the WheelSim heuristic evaluation indicated. These kinds of shortcomings might have a significant impact on the user's performance, in particular if the simulator system is used for training and assessment for real PWC use. Moreover, stereoscopic viewing, despite being a fundamental attribute of VEs and assumed to be particularly important for navigation [1]; was only used in a few studies (e.g. the CAVE system [13]).

The importance of an appropriate visualization environment for simulators was pointed out by many researchers. Kjeldskov [18, p. 78] for example states that: “The potential for immersing the user in a virtual environment is often measured from the field of view". The main problem with desktop monitors is that even though the GFOV is large, the DFOV is much less than the GFOV, which depends on the screen size and the user distance from the screen. Harrison et al. [19] observed that participants preferred large screens over other display types, such as HMDs. The importance of peripheral vision (or lack of it) was also pointed out by [2]. Pithon et al. [14, p. 3] explained that the study of the wheelchair users’ field of view was considered to be an important approach for the design of the visual interface. Thus, our research will investigate three different visualization conditions, a narrow and a wide FOV and a condition with stereoscopic viewing. User-driving performance, sense of presence, and user preference thereby are measured as dependent variables.

III. Material and Methods

A. System

Our system (PWCsim) setup presented in this paper uses a three-sided projection-based visualization and was inspired by the CAVE environment presented in [13]. As the display unit, a wooden frame with laminated plastic stretched all over was used (Fig 2). The frame consisted of three large screens, 100 cm wide and 80 cm high. The main feature of this display unit is that the screen angle between the joint screens is adjustable which allows a similar viewing angle as the virtual camera view provided by the PWCsim software. The simulator system allows three different FOVs. A stereo-FOV with 3D stereoscopic vision on the central screen, a narrow-FOV with 2D monoscopic vision on the central screen and a 2D monoscopic wide-FOV with all three screens used to visualize the virtual environment.

For the wide-FOV three identical regular projectors (Dell 2300MP) were used to present the user’s central and peripheral viewing. These projectors have a native 4:3 aspect ratio with 1024 x 768 pixels screen resolution. A common office PC was used for this wide-FOV. An external multi-display adapter (Matrox TripleHead2Go DP) was used which extended the GFOV to 225° (75° x 3), with a resolution of 3072 x 768 pixels split between the three projectors. The other two conditions (narrow-FOV and stereo-FOV) were run on a laptop computer (Dell Alienware M17x with an Nvidia GeForce GTX 580M graphic board) and displayed by an Epson 3D capable projector (Epson EH-TW6000). Depending on the condition the stereo 3D mode was turned on or off. In the stereo-FOV condition, active shutter 3D glasses had to be worn by the participants. A joystick (Logitech Attack 3) was used to interact with the systems, see Fig 2.

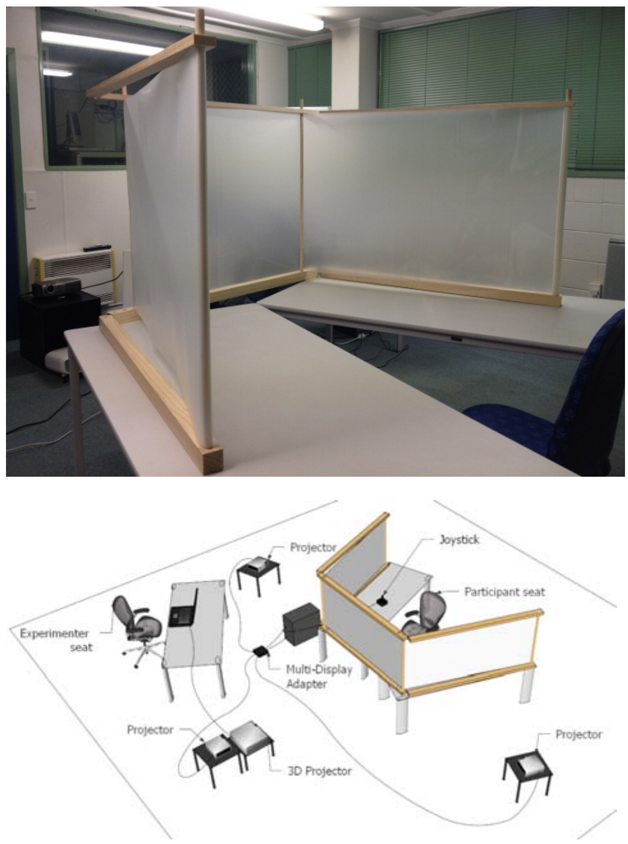

Figure 2. PWCsim projection frame (top) and system setup (bottom)

B. Simulator software Devolopment

Google SketchUp 7 (www.sketchup.com) was used to design the 3D models including the simulator indoor environment (house), virtual PWC, and an ideal path. The dimensions of the indoor environment were considered to meet standards for accessible design [20], in particular doors, corridors, and path width. In this study the door and path widths was set to 120 cm and the corridors to 150 cm. The virtual PWC’s pivot point was placed between the front wheels, which allowed the dynamic interaction of the virtual PWC and correct response to the user motions with the

Joystick. Similar to a real PWC, pushing the joystick further in any direction increases the speed of the virtual PWC and rotates the PWC in that direction. A virtual side-mirror was also implemented that provided a view of the back as well as a virtual joystick that mimicked the movement of the real joystick. Unity 3 was used as graphic engine platform for the simulation, see Fig 3.

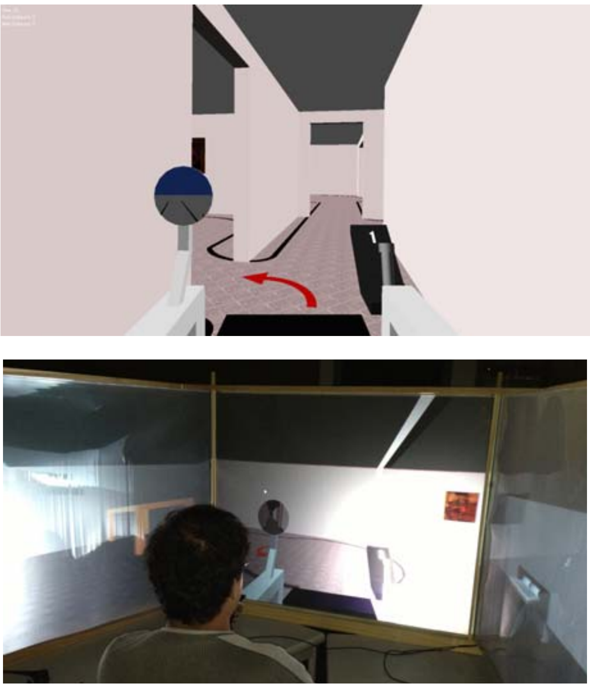

Figure 3. A screenshot of the system (top) and wide-FOV condition (bottom)

C. Participants

The study sample was recruited from students enrolled at the University of Otago. Twenty-four non-clinical subjects (21 male and 3 female) took part in this study. The average age was 23.71 years, ranging from 19 to 31. No participants had vision problems or health issues that would exclude them from participation. None of the participants had used the system before the study was conducted. Upon conclusion of all the sessions, subjects were rewarded with a ten dollar supermarket voucher. This study was approved by the University of Otago Human Ethics Committee and all participants provided written informed consent prior to their participation.

D. Design

In a within-subject experiment design, each participant was asked to perform the same driving task in each of the three visualization conditions (narrow-FOV, wide-FOV, and stereo-FOV) in a randomized and counterbalanced order, where across all participants each visualization was exactly eight times the first, second and third condition. The driving task was to drive as quickly and accurately as possible through an indoor environment by staying within an ideal path (two black lines) and by following directions (red arrows on the floor). The path thereby was conceptualized to contain most of the movements that a PWC user would make in a domestic environment. At each location only the relevant direction information arrows where displayed. Participants were also informed that they could always shift the gears (four speeds) of the virtual PWC using the joystick's fire buttons.

E. Instruments

The users' driving performance was automatically measured in the PWCsim software: total time for completion, number of wall collisions, and number of boundary violations were measured. The driving trajectory was logged at a rate of 10 HZ, while the positions of the path collisions were logged when they occurred. The overall performance score was calculated from the number of path boundary violations (pathViolations), the number of wall collisions (wallCollisions) and the total time in seconds (totalTime) required for the completion of the driving route with Eq. (1). This point score system was adapted from two previous studies [10] and [15], The driving performance score was calculated by assigning 1000 points for each subject and subtracting one point per path collision and one point per second spent. In Additionally two points per wall collision were subtracted - this higher penalty for major mistakes was suggested by WheelSim system [15], and wall collisions are considered as major mistakes compared to path collisions.

$$DrivingPerformance = 1000 - (pathViolations + 2 \times wallCollisions + totalTime) \quad (1)$$

In a post-condition questionnaire the perceived sense of presence and simulator sickness symptoms were measured. Sense of presence was assessed with the IPQ questionnaire [21]. The English version of this questionnaire consists of 13 questions that measure three different factors: involvement (four questions), spatial presence (five questions), and realism (three questions) and contains an additional question to assess general presence. Each question is answered on a 7-point Likert-like scale, ranging from -3 to 3. The overall sense of presence is calculated by averaging the scores from all answers. Four questions related to the confounding variable "simulator sickness" were added at the end of the questionnaire. These questions were taken from the simulator sickness questionnaire (SSQ) introduced by [22] which originally contained questions for 16 symptoms. For this study the symptoms general discomfort, difficulty concentrating, and dizziness (open and closed eyes) were chosen.

A comparative post-study questionnaire was created to directly compare the three conditions from the participants' perspective, regardless of their real performance data. In each question, participants were asked to choose one of the three conditions about how they perceived their experience. The comparative questionnaire was composed of seven questions. Each question had three answers covering narrow-

FOV, wide-FOV and stereo-FOV. Four questions were asked about the users' perceived driving performance, including overall performance, wall collisions, path collisions and time spent. The other three questions asked participants' about their perceived comfort, involvement, and their overall preference.

F. Procedure

Upon arrival, participants were welcomed and asked to sit down comfortably. After the introduction and provided written consent participants were asked to complete a general demographic questionnaire. The information provided in the demographic questionnaire was then used to customise the joystick setup (left or right hand). Participants were also informed that the light would be switched off during each task and switched on upon the completion to enable filling in of the post-condition questionnaires.

The participant started with a training session followed by the actual experiment conditions. In the training session participants received instructions on how to use the joystick and were given the opportunity to practise without any time constraints in a virtual training environment slightly different than the environment used in the experiment conditions. They were also allowed to switch between first and third person perspectives to help them to improve their spatial awareness in the virtual environment. Once the participants were satisfied with their performance, they were asked to do the training task three times, as they would do it in the experiment condition. In the first round, the participants were asked to drive in a first person perspective, in the second round in a third person perspective, and the third round switching between first and third person perspectives. Once they had finished, they were asked if they had any questions and told that they would now start the main part of the experiment.

Before the first visualization was displayed participants were informed about the beforehand randomized order of conditions (e.g. that they would start with the narrow-FOV, than proceed to the wide-FOV, and lastly the Stereo-FOV). They were also reminded again of their task, to drive as fast and accurately as possible and asked to position themselves in a predefined optimal position. After each condition participants were asked to complete a post-condition questionnaire. In the stereo-FOV condition participants were additionally asked to wear 3D shutter glasses, which were adjusted according to participants' preference. Also the level of depth (i.e. the offset between the left and right eye views) was adjusted for those participants based on the participants' preferences (only three out of 24 subjects asked for depth adjustment). A self-report sheet was filled out by the researcher while the participant performed all three conditions. The report was then completed with the participants' verbal feedback gathered at the end of the experiment. The experiment was concluded by informing the participant of their result and the participant was thanked for their participation and rewarded with a supermarket voucher.

G. Statistical Analysis

Experiment data were analysed with IBM SPSS Version 20 using a repeated measures GLM. Within-subject effects and paired-sample t-tests between the results of the three visualization conditions were conducted if appropriate. Significance level was 0.05.

IV. RESULTS

A. Path Boundary Violations

The numbers of path boundary violations in all three settings were close to each other (narrow-FOV: $M = 20.29$, $SD = 10.02$; stereo-FOV: $M = 18.50$, $SD = 11.19$; wide-FOV: $M = 17.17$, $SD = 8.06$). In total, there were 412 violations in the wide-FOV condition, 444 violations in the stereo-FOV, and 487 in the narrow-FOV. No significant differences were found between the conditions $F(2, 46) = 1.22$, $p = .31$.

B. Wall Collisions

The means for the number of wall collisions were also close to each other in the three conditions, with stereo-FOV ($M = 2.63$, $SD = 2.04$), narrow-FOV ($M = 2.96$, $SD = 2.51$) and wide-FOV ($M = 1.96$, $SD = 1.43$). No significant differences were found $F(2, 46) = 1.86$, $p = .17$.

C. Completion Time

The time spent to complete the task was different between visualization conditions. Participants needed less time to navigate through the environment with the wide-FOV ($M = 51.55$, $SD = 11.70$), followed by the narrow-FOV ($M = 55.53$, $SD = 18.26$) and stereo-FOV ($M = 58.67$, $SD = 20.78$). This was confirmed by the results of the statistical analyses which showed that the display setting had a significant effect on the time taken to complete the task $F(2, 46) = 5.25$, $p = .009$ and that there were significant differences between the narrow-FOV and the wide-FOV conditions $t(23) = 2.35$, $p = .028$ as well as between the stereo-FOV and wide-FOV conditions $t(23) = 2.75$, $p = .011$. The difference between narrow-FOV and the stereo-FOV was not significant $p = .174$.

D. Overall Driving Performance Score

The overall performance score was calculated with Equation 1 where a higher score means better performance. The participants achieved highest scores in the wide-FOV ($M = 929.28$, $SD = 16.93$), whereas the means of the narrow-FOV ($M = 918.25$, $SD = 22.83$) and stereo-FOV ($M = 918.25$, $SD = 27.75$) were lower and quite similar to each other. The display type had a significant effect on the overall users driving performance $F(2, 46) = 4.49$, $p = .017$. The wide-FOV condition was significantly higher than the other two conditions with $t(23)=-3.18$, $p = .004$ compared to the narrow-FOV and $t(23)=2.3$, $p = .031$ compared to the stereo-FOV respectively. The difference between the narrow-FOV and the stereo-FOV was not significant $p = .853$.

E. Sense of Presence

Participants felt more present in the wide-FOV (M = .90, SD = 1.36), than in the stereo-FOV (M = 0.38, SD = 1.31), and narrow-FOV (M = -0.28, SD = 1.13). The effects of the display type on the overall users' sense of presence were significant $F(2, 46) = 17.46$, $p < .001$. There were also significant differences between all the condition: between the narrow and stereo conditions $t(23) = 3.20$, $p = .004$, between the wide and narrow conditions $t(23) = 5.78$, $p < .001$, and between the wide and stereo conditions $t(23) = 2.76$, $p = .011$

F. Simulator Sickness

Simulator sickness as a confounding variable was measured with four questions from the simulator sickness questionnaire (SSQ). The average scores for each condition indicate that the degree of experienced simulator sickness was very low (Narrow-FOV: M = 0.18, Wide-FOV: M = 0.42, Stereo-FOV: M = 0.17 on a 4 point scale ranging from 0 to 3). Only one participant experienced a moderate degree of sickness in the wide-FOV condition as indicated with a score of 2.25.

G. Preference

In the comparative questions where participants had to choose which of the three conditions they preferred, 20 out of the 24 participants (83.33%) chose the wide-FOV condition as their preferred system, three participants the stereo-FOV (12.5%) and only one chose the narrow-FOV (4.17%). The preference for the wide-FOV was also indicated by the participants' responses favouring the wide-FOV condition (43.75%) in their judgment on their average perceived driving performance (compared to narrow-FOV: 25% and stereo-FOV: 31.25%), in perceived comfort (wide-FOV: 70.83%, narrow-FOV: 16.67, stereo-FOV: 12.5%) and perceived involvement (wide-FOV: 79.17%, narrow-FOV: 0% , stereo-FOV: 20.83%).

V. DISCUSSION AND CONCLUSION

This research identified possible factors (FOVs and display types) that influence users' driving performance and sense of presence and compared them in a PWC simulator. It was found that participant's overall performance (calculated from the collisions and completion time) was best in the wide-FOV compared to the narrow- and stereo-FOV. The wide-FOV was also the participant's preferred viewing condition and elicited as the strongest sense of presence. The findings that we have identified can assist in the building of better simulators, in particular PWC simulators. The present study, also, makes several noteworthy contributions to the realm of PWC simulators. First, it made use of the simulator data to assess individual driving performances. Second, it made use of some of the data to visualize user performance, such as the locations of the path collisions and user trajectories. Third, the interaction technique "Travel" (Bowman et al, 2005) chosen for this simulator proved to be easy to follow and represent reality. The data recorded from the simulator and later presented in a visual form, such as path collision locations and user trajectories could also be used by therapists to strengthen their educated guesses, or support the simulator assessment results. It could also be used to assess wheelchair accessibility especially during the design of new buildings.

A number of limitations need to be acknowledged that should be addressed in future studies. A future study would need to show if the findings from the able-bodied participants in this study can be replicated with actual or potential wheelchair user groups. Comments by several participants that the display was too bright and the colour needed to be improved indicated a limitation related to the material used (laminated plastic) to display the projected video. The lack of sound, such as PWC engine sound, in the simulator was also brought up. These issues should be resolved before the commencement of future studies. Furthermore, the incorporation of haptic or vestibular feedback into the system should be considered.

This research has raised many questions that necessitate further investigation. The current study investigated two main factors that influence driving performance in a PWC simulator, these being field of view and display type, but further research can be widened to investigate other factors. A condition that was not addressed in this study was whether a combination of wide field of view and stereoscopic vision in the center will influence user driving performance and sense of presence. User driving performance could also be looked at from different perspectives. Some examples include different virtual environments, such as indoor and outdoor, or different navigation tasks. These areas would establish a base for better understanding of PWC simulators. In terms of simulator design, more research into physical simulation, interaction, and visualization is important and it is actually the first step towards a reliable assessment and training simulation.

The following conclusions can be drawn from the present study: that the wide field of view could be a promising interface for complementing training or assessment of PWC users. The outcome of this research should not only benefit PWC simulator designers or developers, but also contribute to other fields of study in terms of visualization and interaction, such as simulation systems, game design, navigation systems, computer graphics, etc. Given the results of the user performance, sense of presence, and preference of the display types should assist on selecting the right display for targeted people. The study findings might also be applicable to other kinds of vehicle simulators as well, for example, virtual cars, airplanes, vessels, and bicycles.

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