Impact of the visual representation of the input device on driving performance in a power wheelchair simulator

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ABSTRACT

Virtual reality-based power wheelchair simulators can help potential users to be assessed and trained in a safe and controlled environment. Although now widely used and researched for several decades, many properties of virtual environments are still not yet fully understood. In this study, we evaluated the effects of the visual representation of the input device in a virtual power wheelchair simulator. We compared the virtual display of a standard gaming joystick with that of a proprietary power wheelchair joystick while users used either of the real world counterparts, and measured the effects on driving performance and experience. Four experimental conditions comprising two visual virtual input modalities and their two real counterparts as independent variables have been studied. The results of the study with 48 participants showed that the best performance was obtained for two of three performance indicators when a virtual representation of the PWC joystick was displayed, regardless of what type of joystick (real PWC or gaming joystick) was actually physically used. Despite not explicitly being made aware of by the experimenter, participants reported noticing the change in the visual representation of the joysticks during the experiment. This supports the theory that the effects of virtual reality representations have a significant impact on the user experience or performance, and visual properties need to be carefully selected. This is specifically important for applications where the transfer effects to real world scenarios is sought and ecological valid simulation is aimed for.

1. INTRODUCTION

Power wheelchairs (PWCs) can improve users' quality of life by enabling them to participate in daily living activities and decrease their dependence on human assistance (Lee, 2014). PWC users have to deal with restricted environments involving limited space to manoeuvre and are therefore vulnerable to collisions and injuries. Therefore, to use a PWC effectively and safely, individuals have to undertake training and an assessment of their competency. Swan et al. (1994) reported 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". This has increased the need for better PWC simulations in order to train users to develop more expertise in driving PWCs and to assess user competency.

This has triggered researchers to investigate systems that could help to overcome the limitations of traditional PWC assessment and training. Already in the 1980s, Pronk et al. (1980) built a first system to help PWC users to adapt to actual PWCs. They concluded that such a simulation could help with the adaption and/or evaluation of PWC users. Subsequently more studies to evaluate the driving skills of PWC users were conducted. For example Cooper et al. (2005) measured completion time, number of path boundary violations, and errors between virtual PWC trajectory and desired path and concluded that such data could be useful in assessing and/or training PWC users. Moreover, they noted that a very important aspect of driving a PWC is the input device where the suitability can be objectively assessed through simulation. Previous research show several advantages of using a PWC simulator: potential utility as an assessment and/or training device, positive skills transfer from VEs to real environments, and objective measures of user performance easily generated by the simulator. These measures can be summarized as number of collisions either with objects or path boundaries, time spent, user trajectories, and combinations of these criteria to formulate a score.

Unfortunately there is a lack of commercially available PWC simulators outside of research that are appropriate for assessment and training (Abellard et al., 2010). Although commercial PWC software (WheelSim) exists, it is deemed unsuitable as a training and assessment system. In a usability inspection, Alshaer et al. (2013) detected severe shortcomings that make it unsuitable for use as a training and/or assessment system. Flaws identified by the authors were: 1) lack of an accurate physical simulation, 2) unknown size and driving speed of the PWC, and 3) inaccurate joystick interaction because the virtual PWC did not move and accelerate accordingly. Furthermore, pure software solutions still require the use of appropriate hardware as input devices which again could cause unwanted results if they are not specific to the software.

Building a realistic and effective virtual-reality-based environment requires the consideration of many factors. Two overview papers by Schuler et al. (2014, 2015) show that movement visualization, feedback and context information can have a significant impact on the user experience as well as on therapy outcomes for patients. This can also apply to virtual-reality-based vehicle simulators such as power wheelchair (PWC) simulators where correct physical simulation, realistic 3D modelling of the environment and the PWC, provision and/or simulation of the physical environment, and an appropriate interaction device may impact user experience and the functionality of the system. An essential hardware component of PWCs is usually a finger-operated joystick. Because actual PWC joysticks are proprietary and expensive, PWC simulators often use commercial gaming joysticks to interact with the simulator (Alshaer et al., 2013; Archambault et al., 2012) or adapted PWC joysticks (Hasdai et al. 1998; Adelola et al., 2002; Harrison et al. 2002).

Previous research has evaluated different input devices for different applications, either from a usability point of view, or in terms of performance. Rupp et al. (2015) report that the wrong input device: "can affect performance, increase cognitive workload and increase errors that may lead to the loss of a vehicle". However, none of the previous PWC simulation studies have investigated the impact of using a PWC joystick compared to a gaming joystick. In fact, this also raises the question of the virtual representations of these input devices. According to Powell & Powell (2014), small changes in the virtual representation of the geometry of objects has an effect on the user experience and affects the perception of spatial location. This was demonstrated in their study where participants were asked to reach and grasp three different shapes in a VE (apple, sphere, and polyhedron) and measured the time participants took to reach the target. They found that users preformed significantly slower to locate and grasp a sphere compared to a polyhedron of the same size. This would indicate that the design of virtual objects, such as PWC components, could have a substantial effect on the performance of users and therefore influence the training and assessment outcomes in PWC simulations.

Our goal in this study is to evaluate the effects of the combination of virtual and real power wheelchair joysticks in the form of a proprietary power wheelchair joystick and a standard gaming joystick. Would one be perceived better than the other and therefore lead to better performance and experience? To our knowledge, this is the first study to investigate the visualization of the input device, in particular, if different input devices are used. In this study, we compared the virtual display of a standard gaming joystick and that of a proprietary power wheelchair joystick in combinations with their real world counterparts. The impact was assessed in the context of driving performance, where users' path and wall collisions, and completion times were recorded as participants drove a simulated PWC. In addition, participants reported on their experience and awareness. This study aims to provide information to help designers/developers to create optimised PWC simulations and extend the knowledge on the effects of visual representation in VE on user performance.

2. METHOD

2.1 Participants

The study sample was recruited from people who attended the science festival at Otago University, New Zealand. We performed a statistical power analysis to estimate the required sample size before running the experiment. We used effect size from a similar previous experiment (Alshaer et al., 2013) to calculate the required sample size using the power analysis and the required sample size to detect differences was calculated to be 40. We recruited 48 participants (31 males, 17 females). Two participants data were not analysed, as they were the only two left-handed. The age range of the 48 participants was 18 to 73 years old, with a mean age of 34 (SD=11.97). Participants were also asked about their joystick experience before the experiment to determine how much information/training participants should receive before conducting the experiment. None of the participants were actual power wheelchair users.

2.2 Apparatus

Two aspects of the virtual reality (VR) simulation were considered: (1) the actual joystick, physically operated by the user, and (2) the virtual representation of the joystick within the virtual environment. Two popular joysticks were selected to be evaluated: a standard off-the-shelf gaming joystick (Logitech Attack 3) which is affordable and available in the gaming accessories market, and an expensive, purpose-built PWC joystick (Q-Logic control) which is used on many power wheelchairs and only works with PWC (Figure 1). Due to the specialist design of the PWC joystick, we modified it for use with USB input. To achieve this, an Arduino-based LeoStick (www.freetronics.com/products/leostick) board was electronically connected, programmed, and calibrated to read the PWC joystick outputs. These outputs were then mapped to function in the virtual environment. Hence, both the PWC and the gaming joystick worked the same for the user.

For the virtual joystick representations, realistic 3D designs for both the gaming joystick and the PWC joystick were modelled (see Figure 1). In addition, the physical movements of both joysticks were simulated. The 2 degree-of-freedom deflection of the joysticks were mimicked in the virtual representation in the VE. Therefore, pushing the joystick in any direction will immediately be visualized within the VE according to the participant's movements. As with a real PWC, pushing the joystick further in any direction increases the speed of the virtual PWC and rotates the PWC in the direction pushed. None of the joysticks' buttons were used in this experiment.

Figure 1. *Real PWC and gaming joysticks (left). Virtual PWC and gaming joysticks (right).*

Both joysticks were placed on a wooden frame so that the participant's hand position was similar to that in a PWC (Figure 2). Both joysticks were connected to a laptop via USB. We used a 17″ Alienware high-end graphics laptop to run the simulator with a resolution of 1,920 × 1,080 pixels at 120Hz. Google SketchUp was used to design the 3D models, including the indoor environment (house), the virtual mid-wheel PWC, the virtual gaming and PWC joysticks, and the ideal path to be followed by our participants. Unity3D was used as the graphic engine platform for the simulation, which provides also the physics simulation capabilities.

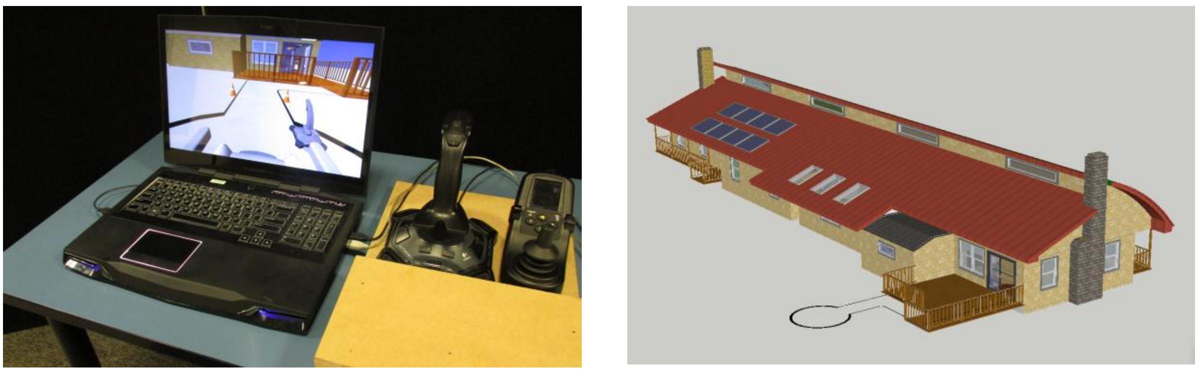

Figure 2. *(On the left) experiment setup: Alienware laptop, gaming joystick, and PWC joystick; (on the right) outside view of the house environment used in our simulation.*

2.3 Environments and Driving Task

A domestic environment (Figure 2) was used for the simulation. The environment was built to meet the Americans with Disabilities Act (ADA) ("Americans with Disabilities Act of 1990, as amended," n.d.)' standards for accessible design. The effective width for internal doors accessed from corridors was 1.2 m and the corridor's minimum width was 1.5 m to facilitate 360° turning (Desmyter, Garvin, Lefèbvre, Stirano, & Vaturi, 2010). The user task was to drive as quickly and accurately as possible through this indoor environment by following an ideal path (driving between two black lines). The path was devised to contain most of the movements a PWC user would make in a domestic environment. These movements were inspired by the wheelchair skills test (WST). The WST is a set of assessment and training protocols developed by Dalhousie University (http://www.wheelchairskillsprogram.ca/eng/). Yellow arrows were placed on the path pointing in the direction of movement. The task (path following) was used in a previous study (Alshaer et al., 2013) and yielded a sufficiently variable performance.

2.4 Measures

For user performance, the following objective metrics were measured per condition: completion time, path boundary violations (when any of the PWC's wheels went beyond one of the black lines), and wall collisions. 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 using Eq. (1). The scoring system was used in (Alshaer et al., 2013), which was also inspired by Abellard et al. (2010), Hasdai et al. (1998), and WheelSim (2007).

$$\text{Score} = 1000 - (\text{pathViolations} + 2 \times \text{wallCollisions} + \text{totalTime}) \tag{1}$$

To measure user experience and awareness, we developed four questions consisting of seven-point Likert scale items where "-3" means "strongly disagree" and "3" means "strongly agree". The aim of these questions was to obtain participants' experience and therefore were asked once after completion of all conditions. The four questions were as follows:

- *Q1:* Overall, I felt as though I was operating the virtual joystick presented on the screen
- *Q2:* Overall, I felt as though I was operating the physical joystick in my hand
- *Q3:* Overall, I was aware of the switching between the virtual joysticks
- *Q4:* Overall, I was aware of the differences between the joystick on the screen and the one in my hand

2.5 Experiment Design

We used a 2 (physical joystick: PWC v Gaming) X 2 (virtual joystick: PWC v Gaming) within-subjects factorial design: the physical joystick handled by the participant (Attack 3 Gaming or Q-Logic Control PWC) and the virtual joystick represented on the screen (Attack 3 Gaming or Q-Logic Control PWC). This yielded four conditions as shown in Table 1.

Table 1. *2×2 factorial design.*

		Physical Joysticks	
		Gaming	PWC
Virtual Joysticks	Virtual Gaming	G-vG	P-vG
	Virtual PWC	G-vP	P-vP

2.6 Counterbalancing

Due to a potential learning effect associated with repeating of the task four times we controlled for ordering effects. First, subjects were randomized in counterbalanced order. Second, although subjects repeated the tasks four times, they were generally unaware of the repetition. The participants followed one layout on a return path, which created a balanced set of comparable paths that the user could traverse without interruption (Figure 4). The users couldn't really predict what was coming next, e.g. it was hard for them to know which direction to travel next as the right turn became left when driving in the reverse direction. In addition, the condition order set was randomized based on Latin Square counterbalancing.

2.7 Procedure

The experiment was run during a local science exhibition where participants, including school and university students, university staff, and the general public, came to participate in a wide range of scientific activities. All visitors were free to take part in any of the available activities. Upon arrival, participants were welcomed and consent was obtained electronically by clicking 'YES' if they wanted to be part of the experiment.

Participants were informed about the type of the virtual PWC (mid-wheel) and how it moved. They also received instructions on how to use the joystick and were given the opportunity to practice before starting the task. Once participants were ready to start, they were reminded of the task (driving as fast and accurately as possible). They were also told that they would be using two different joysticks and would see virtual counterpart representations in the VE. They were told to follow the ideal path, and stop if they saw a stop sign. Switching between virtual joysticks was done automatically through the simulator depending on the condition order set. When a stop sign appeared on the screen, participants were asked to switch between the physical joysticks. The stop sign appeared according to the condition order as well. At the end, participants were asked to fill in a demographic questionnaire and "overall" perception/awareness questionnaire (four questions).

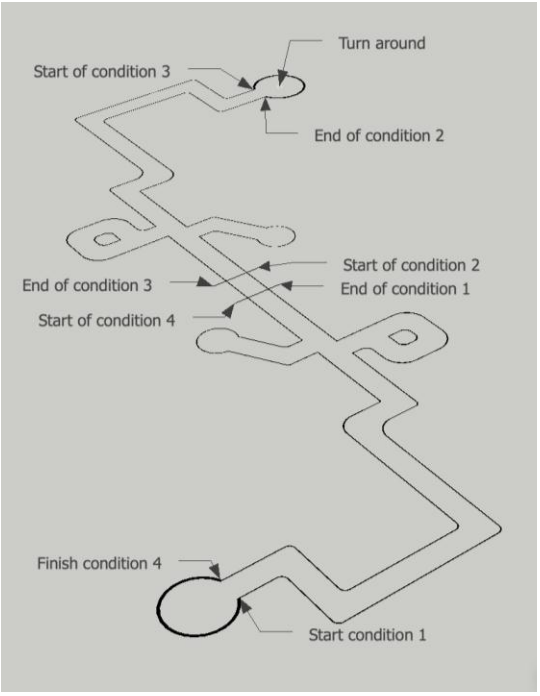

Figure 4. *Ideal path through the environment.*

3. RESULTS & DISCUSSION

3.1 Objective Metrics

*3.1.1 Path Boundary Violations.*The means of path boundary violations (driving beyond the black lines), together with standard deviations are reported in Table 2. A two-way, repeated-measures ANOVA was performed. The results showed that neither physical joysticks nor the interaction between physical and virtual joysticks had a significant main effect, but that virtual joysticks had a significant effect where participants had fewer path collisions when the virtual PWC joystick was represented ($F(1, 47) = 4.513$, $p < 0.039$, $\omega2 = 0.088$).

3.1.2 Wall Collisions. The means of wall collisions, together with standard deviations are reported in Table 2. A two-way, repeated-measures ANOVA was performed. The results indicated that the virtual joystick had a significant effect ($F(1, 47) = 7.009$, $p < 0.011$, $\omega2 = 0.130$) with participants performing better when the PWC virtual joystick was represented. Neither the physical joystick nor the interaction between the physical and virtual joystick had significant effects on the number of wall collisions.

3.1.3 Completion Time. The means of completion time, together with standard deviations are reported in Table 2. The time spent to complete the task was similar between each condition. Two-way, repeated-measures ANOVA was performed, but neither of the independent variables nor the interaction between them had significant effects on the participants' completion time.

3.1.4 Overall Driving Performance Score. The means of overall driving performance, together with standard deviations are reported in Table 2. The overall performance score was calculated with Equation 1 where a higher score indicated a better performance. A two-way, repeated-measures ANOVA was performed, but neither of the independent variables nor the interaction between them had significant effects on the participants' overall driving performance score.

Table 2. *Means and standard deviations for all objective metrics.*

Path boundary violations

		Physical Joystick: Gaming	Physical Joystick: PWC	
Virtual Joystick	Gaming	13.27 (9.75)	10.48 (.73)	11.88
	PWC	10.71 (7.81)	9.42 (8.43)	10.06
		11.99	9.94	

Wall collisions

		Physical Joystick: Gaming	Physical Joystick: PWC	
Virtual Joystick	Gaming	2.50 (2.24)	1.81 (2.09)	2.15
	PWC	1.65 (2.22)	1.65 (2.19)	1.65
		2.08	1.73	

Completion time

		Physical Joystick: Gaming	Physical Joystick: PWC	
Virtual Joystick	Gaming	57.35 (12.95)	58.42 (12.49)	57.89
	PWC	56.75 (14.18)	58.94 (14.32)	57.84
		57.05	58.68	

Overall driving performance score

		Physical Joystick: Gaming	Physical Joystick: PWC	
Virtual Joystick	Gaming	924.37 (19.68)	927.46 (18.75)	925.92
	PWC	929.24 (17.15)	928 (19.65)	928.62
		926.81	927.73	

3.2 Subjective Metrics

For the experience and awareness questions (Figure 5), a Wilcoxon signed rank test was performed against the midpoint (0) to see if the participants agreed or disagreed with the statements. Although participant answers to question 1 ("Overall, I felt as though I was operating the virtual joystick presented on the screen") was slightly above the midpoint (M= 0.1, SD= 1.88), the one sample Wilcoxon test did not show a significant difference. On the other hand, the test showed a significant difference on question 2 ("Overall, I felt as though I was operating the physical joystick in my hand", $p < 0.000$, with (M=2.15, SD = 1.11). A Wilcoxon Signed-Ranks test was performed to compare responses on the two questions. The analysis showed a significant main difference in favour of the physical joystick. Responses to both questions (Q3. "Overall, I was aware of the switching between the virtual joysticks" and Q4. "Overall, I was aware of the differences between the joystick on the screen and the one in my hand") were above midpoint (M= 1.04, SD= 2.0, and M= 0.85, SD= 1.86 respectively). Both questions showed significant effects p= 0.002 for Q3, p = 0.003 for Q4. A Wilcoxon Signed-Ranks test was performed to compare responses on the two questions. There was no main difference between the two questions.

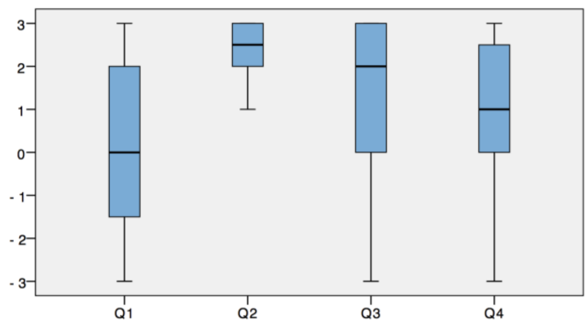

Figure 5. *Participants' answers to experience and awareness questions.*

4. CONCLUSIONS & FUTURE WORK

In this study, we evaluated the effects of visual representation of input devices in a virtual power wheelchair simulator. We compared the virtual display of a standard gaming joystick to a proprietary power wheelchair joystick while users used either of the real world counterparts. We measured the effects on driving performance and reported experience. Our results showed that for two of three performance metrics driving performance is significantly affected by the form of the virtual joysticks, but not by the type of physical joystick used. This indicates that performance can be influenced by changing visual properties, such as, the type of input device visualised. It also indicates that for the use in a virtual PWC simulator a rather inexpensive gaming joystick might be adequate.

The results of the study suggest that users of the simulator paid attention to the visual representation of the joystick and used it to guide their control of the PWC. We believe that the differences in the driving performance between the two virtual representations of the joystick is due to the level of how participants deduced steering information from the position of virtual joystick's handle. While the PWC joystick is equipped with a straight handle, the gaming joystick has a curved handle pointing forward on the top (Figure 1). This property of the gaming joystick could make it more difficult for participants to notice visual differences between small forward or backward positions of the handle and therefore impede the inclusion of this information in steering decisions; on the other hand, the properly aligned virtual joystick may help to enhance the participants' sense of alignment of the physical joystick. This might have led to better performance, in particular with novice participants. Another explanation could be that the virtual gaming joystick was an out-of-place distraction due to its size in the VE compared to the smaller virtual PWC joystick. Therefore, paying attention to the virtual game joystick degrades performance in a way that the PWC joystick does not.

Future studies may also investigate whether the effects were related to visual dominance theory (Posner, Nissen, & Klein, 1976), a felt sense of presence in the environment or both. The visual effect could be investigated more by tracking the user's eyes to determine when and how much time individuals would look directly at the virtual joystick. Moreover, the particular way in which we present the virtual joystick offers a convenient view of the input state near the centre of the display. A larger display could be used so that the physical joystick could be placed and viewed in the same relation to the virtual scene as the virtual joystick. Future studies could also investigate avatar-related conditions where the user's body or body parts are varied in their presence and visualisation characteristics. The participants used in this study were a convenience sample. This enabled us to meet the power requirements for the study. In addition, their unfamiliarity with PWCs and their proprietary joystick controller enhanced the internal validity of the study. The question of external validity or generalizability to the population of wheelchair users remains open for further investigation. Considerable variability in performance was evident between participants, so future studies might consider longer session times or repeated sessions and measures in combination with larger sample sizes.

Our findings suggest that visual properties of input devices represented in the virtual environment need to be carefully selected and chosen specifically for applications where the transfer effects to real world scenarios is sought and ecological valid simulation is aimed for. It also provides guidance on which VR input devices are necessary and appropriate and which virtual device representations can and should be implemented for power wheelchair simulators. In addition, with our simulator we have laid the foundations for a more comprehensive power wheelchair simulation system, including aspects of the use of simulator data to assess individual driving performance, correct physical simulation of power wheelchairs, and to take into account appropriate dimensions of an indoor environment to meet the standards for accessible design. This study provides an interesting test bed for future investigations.

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