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A standardised and cost-effective VR approach for powered wheelchair training

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ABSTRACT Mastering wheelchair driving skills is essential for the safety of wheelchair users (WUs), yet the acquisition of these skills can be challenging, and training resources can be costly or not available. Technologies such as virtual reality (VR) have grown in popularity as they can provide a motivating training environment without the risks found in real-life training. However, these approaches often deploy navigation controllers which are different from the ones WUs utilise, and do not use a standardised approach in assessing the acquisition of skills. We propose a VR training system based on the wheelchair skills training program (WSTP) and utilizing a sensor device that can be retrofitted to any joystick and communicates wirelessly with a Head-Mounted Display. In this paper, we present a first-validation study with fourteen able-bodied participants, split between a VR test group and a non-VR control group. To determine the acquisition of skills, participants complete tasks in real-life before and after the VR training, where completion time and length of joystick movements are measured. We also assess our system using heart rate measurements, the WSTP questionnaire, the simulator sickness questionnaire and the igroup presence questionnaire. We found that the VR training facilitates the acquisition of skills for more challenging tasks; thus, our system has the potential of being used for training skills of powered wheelchair users, with the benefit of conducting the training in safely and in a low-cost setup.

INDEX TERMS assistive technologies for persons with disabilities, emerging technologies, sensors, virtual reality.

I. INTRODUCTION

According to the World Health Organization (WHO) over 70 million people require the aid of a wheelchair to gain mobility [1]. When someone goes from being able bodied to using a wheelchair, they need to learn specific skills have such as propulsion techniques and navigating through barriers; these skills should be taught via a initial rehabilitation programme [2] to enable new Wheelchair Users (WUs) to drive the wheelchair safely, to manage their daily activities and, therefore, to improve their independence [2] [3], [4]. Importantly, training enables WUs to avoid being placed in long-term care facilities [5], [6] , participate in society [5], [7], [8], [9], and return to work [5], [10] .

Traditionally, training involves completing tasks, such as obstacle courses [11], within controlled environments; the Wheelchair Skills Training Programme (WSTP) [12] is a popular and standardised real-life training that enhances and assesses skills of WUs on individual tasks (e.g. driving straight, backwards, through obstacles, turning etc.) However, these traditional training methods can be expensive and requires time and resources that are often not available [13], [14].

Research has been done to investigate how the application of new technologies can mitigate the shortcomings of traditional training [11]. Virtual Reality (VR) has recently attracted attention in the field of rehabilitation, including wheelchair skills training [11]. Studies on VR training for wheelchair users date back to the 1990s, as reported by the review paper [14], which has investigated the effectiveness of VR training methods. VR can have numerous benefits: it can be motivating, it mitigates the physical risks faced in the real-world training [15], it increases independent learning opportunities, and it enhances engagement with tasks [16].

The immersion and involvement in a VR environment elicit the Sense of Presence (SoP), defined as "experiencing the computer-generated environment rather than the actual physical locale", which positively correlates with the effectiveness of VR based training [17], [18]. Depending on the complexity of the VR system, VR minimizes outside distraction while stimulating the users' senses to enhance the learning experience by targeting various feedback mechanisms such as auditory, visual, vestibular and force feedback [19].

However, VR training programs normally use joysticks specific to a certain wheelchair [14], or gaming joysticks [14]. These joysticks might not accurately represent what a person uses in their day-to-day life, and it is important that WUs get acquainted to the joystick of their own chair. Furthermore, to date, most VR training programs require the help of a clinician [14], and thus they cannot be conducted independently. These factors may restrict the accessibility of VR training. Importantly, due to the heterogeneity of the VR training methods currently available [14], [18], it is unclear what approach best leads to the acquisition of skills in real life. Thus, there is the need for a VR wheelchair training system that is affordable, user-friendly and which can be used in the comfort of one's own chair and crucially, a system that deploys a standardised approach to assess the actual acquisition of skills.

This paper presents our first study in the development of a VR-based system for the training and assessment of wheelchair driving skills, with low-cost equipment that can be used beyond a clinical and experimental setting. We hypothesise, firstly, that VR training leads to acquisition of skills in real life, and we propose a standardised assessment based on the improvement in the user's completion time and in the length of joystick movements in various tasks performed in real-life (see section 3.5), before and after completing the same tasks in VR.

Secondly, we hypothesise that a low-technology can still deliver an effective training. To address the affordability of wheelchair training, whilst giving WUs an experience that closely mimics their day-to-day driving experience, we use an inertial measurement unit (IMU) sensor to navigate in VR. The sensor is retrofitted to the joystick of a wheelchair, allowing the participants to use the same wheelchair for the real-life and for the VR training.

As our system consists in completing various tasks, it is important to acknowledge that different tasks have different psychophysical load, which is believed to be related to changes in heart rate (HR) [20], [21]. Malinska et al. [20] believe that with the VR's increase in popularity, there is a need to find out how it affects the HR regulatory mechanism. Thus, during our training in VR, we to look for any significant difference in HR of the user between tasks. By doing so, we aim to assess whether changes in HR, and therefore in psychophysical load, are related to performance improvement.

We also use three different questionnaires to assess our system: the Wheelchair Skills Training Questionnaire [22] to analyse the user's confidence in their skills; the iGroup Presence Questionnaire [23] to assess the presence and realism elicited by our system; the Simulator Sickness Questionnaire [24] to measure the level of cybersickness.

The structure of the paper is as follows: Section 2 discusses previous related work and how our study builds on it. Section 3 describes the methodology of our study. Sections 4 presents the results, which are discussed in Section 5. Finally, the paper ends with our conclusions and future work (Section 6).

II. RELATED WORK

To study previous works, we first investigate literature on how wheelchair skills training is conducted in real life, and how we can implement those methods in a VR system. Then, we investigate the benefits of using affordable technology to create a VR training system.

A. WHEELCHAIR SKILLS TRAINING IN REAL LIFE

Real-life wheelchair skills training can vary in nature, and often consists in completing tasks within controlled environments, such as obstacle courses, and measures speed and time completion to assess improvement [11]. Other methods, though less popular, are 'ecological' in nature where the user drives through real environments, while also interacting with them, such as schools and homes [11] ; the interactions can mimic what someone would do daily like reaching for objects, writing, and opening doors [11], [25]. Due to the heterogeneity of real-life trainings, a way to standardise them has been developed, namely the WSTP [12]. This is for manual and powered wheelchair users and mobility scooters. This programme consists of a set of tasks that a person must be able to successfully complete to be deemed able to drive a wheelchair independently. The efficacy of WSTP in training was analysed by Tu et al. [26] in terms of short-term effects and long-term effects of the WSTP. Tu et al. found that participants undergoing the WSTP showed higher improvement in the short-term (immediately to one-week after) than those undergoing other methods for manual wheelchair users.

A similar review was conducted by Keeler et al. [27]who concluded that the WSTP has a meaningful effect on improvement of skills compared to no training or other methods. The WSTP is also regularly revised and updated, with bootcamps held for occupational therapists to acquire the skills taught in the program [28]. Furthermore, the effectiveness of the WSTP for adults is incentivising its use in pediatric settings [29].

Though the WSTP is an efficient method to train new wheelchair users, real-life training requires a lot of time and resources which are not available to everyone [23]. Further, powered wheelchairs are also heavier than manual ones, and can go at moderately high speeds, thus incidents during training can be very harmful.

B. VIRTUAL REPLICA OF THE WSTP

The body of literature concerning wheelchair skills training in VR reported a lack of standardised tasks and assessment [11], [14], [18]. As a result, Lam et al. [14], suggests the use of the virtual replica of the wheelchair skills test (WST) to assess the user's driving capacity, normally used in the Wheelchair Skills Training Programme (WSTP) [12]. The use of this program in real life has shown an increase in short-term retention of skills compared to participants undergoing other training methods [26], [27]. This motivates us to follow Lam et al. [14] suggestion to recreate the WSTP in VR.

The virtual replication of some of the skills of the WSTP (namely rolling forwards, turning 90◦ while moving forward, turning in place) has been done by Devigne et al. [30]. The VE was developed using Unity3D and the training was performed using a semi-immersive modality, namely the CAVE system. However, the WSTP tasks were performed prior to the actual training, which consisted of obstacle courses.

The use of the WSTP as a virtual training tool was studied by Archambault et al. [31], who based their system on the following tasks: driving backward 5m in a straight line, opening a door, moving through the door-way and closing it (in both directions, pushing and pulling), turning 180° within the limits of a 1.5 m square (left and right), turning 90° forward (left and right), turning 90° backward (left and right), and moving sideways from one wall to another in a 1.5 m square (left and right). All the tasks were performed five times in each direction (e.g. left and right). The tasks were conducted in a virtual replica of a clinical setting, developed using the miWe simulator and shown on a desktop display. To validate the effectiveness of VR, two groups of participants took place in the study, one performing said tasks in VR and one in real life, with their performances being compared in terms of joystick amplitude, trajectory and completion time. Their results seemed promising, with the authors suggesting their simulator has the potential to be used in rehabilitation centres. However, the results were not validated in terms of improvement of driving manouvers after conducting the VR training and the use of a desktop monitor for training has been found to be less effective than the use of a Head-Mounted-Display (HMD) [32] .

The WSTP tasks were also employed in a study conducted by Fraudet et al. [33] in which the authors aimed to evaluate the user tolerance and driving performance of a powered wheelchair in VR versus real life. Participants came in for three separate sessions, each in growing levels of difficulty, and completed a set of tasks both in VR and in real life. The VR tasks were modelled using Unity3D and were a replica of the ones conducted in real life. The session included tasks such as driving forward (10m) and backwards (2m), turning in place while moving forwards (90°). The second session was more difficult and included getting through a hinged door, ascending and descending 5° access ramp, rolling on soft surface (2m), crossing a threshold and driving through narrow corridors. The third session was the most difficult where participants had to avoid moving obstacles, ascending and descending 10° access ramp. This study was not used to teach participants wheelchair driving skills, as the participants were already expert wheelchair users. However, it validates the use of the WSTP in VR as its results demonstrate participants adapted quickly to VR and their performance was similar to the real-life one. The authors also concluded that the use of VR can be a beneficial tool to acquire powered wheelchair driving skills for patients unable to practice these skills safely in real life.

C. AFFORDABLE TECHNOLOGY FOR DRIVING SIMULATION

The majority of the VR wheelchair training systems are controlled via a joystick, whether that is a real powered wheelchair joystick [14] or a gaming one [14]. There are exceptions that use other training systems, such as eye-tracking [34], sensors on the wheels [25], brain computer interface [35] or a mechanical platform in the case of manual wheelchairs [36]. However, the current VR training systems do not accommodate for the user's comfort of using their own wheelchair and joystick. Gaming joysticks do not necessarily replicate the mechanisms of a wheelchair joystick, while in cases where a wheelchair joystick is used it may be a different one than the joystick WUs utilize in their day-to-day life. Further, to use the signals of a real wheelchair joystick as a navigation tool in VR, the joystick has to be "hacked" to send movement signals to the VR system. Thus, a training system could be more effective and convenient, if it was adaptable to a variety of joysticks. To our knowledge, no studies have examined novel approaches to help users gain a VR training using their own wheelchairs, using affordable equipment that can be used "anywhere anytime".

The use of IMU sensors has been a topic of research when it comes to driving a wheelchair in real life, by attaching the sensor to a person's body parts. Kundu et al. [37] proposed a system that uses the 'SEN10736' IMU sensor, specifically its accelerometer data, to drive a wheelchair with hand gesture recognition. Nirmala et al. [38] also proposed a gesture-controlled wheelchair, with the goal of keeping it low-cost using the ADXL335 accelerometer. Similarly, Farin et al. [39] and Haque at al. [40] used accelerometers (the ADXL335 and ADLX345, respectively), to control the wheelchair with head movements, rather than hand movements

Having a sensor attached to a joystick, also allows for an analysis of the user's skills by determining improvement based on the joystick's behaviour. Hernandez-Hossa et al. [34] developed a VR training and validated the effectiveness of its system by looking at the number of

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joystick movements, for which they used a classifying algorithm for the joystick's analogue signals to determine direction of navigation (forward, backward, right, left). Similarly, Archambault et al. [31] measured the joystick's amplitudes to determine improvement in number of joystick signals, however their joystick interface was not the one of a real powered wheelchair. Measuring improvement in joystick behaviour can indeed be an indicator of acquisition of skills, as Sorrento et al. [41] found that expert wheelchair users require less manoeuvres in difficult tasks than novice users.

III. METHODS AND TOOLS

For our study we developed a system to train wheelchair users; the system consists of an in-house VR environment using the Unity 3D game development platform [42], an in-house hardware unit consisting of IMU sensors to navigate in the VR environment, the Oculus Quest 2 HMD (with a display resolution of 1832x1920 per eye, and a refresh rate of 72Hz) connected to a Microsoft PC (specifically the ROG Zephyrus M16 running on Windows 11 with Intel i9-12900H processor, GeForce RTX 3080Ti NVIDIA GPU and 32GB DDR5 RAM) and a heart-sensor (Polar H10). We propose using the MPU-9250 retrofitted to a wheelchair joystick, the Dx2-REM550/551, to navigate in our VR environment. We believe this way the navigation system can be adapted to a variety of joysticks, and as such also be used remotely.

The study involved in participants being split into *a non-VR control* group and a *VR test* group, and individually coming in for two separate sessions. In the first session, both groups completed real life wheelchair driving tasks. In the second session the control group repeated the same tasks while the VR group first performed a set of tasks in VR and then repeated the tasks of the first session. The following sub-section provides details of the system we developed and used, and details of the study we conducted.

The following subsections detail how the study was performed. First the setup of the study is described, followed by a block diagram (Fig. 1). Then, the details of the real-life exercises and the virtual environment are given, followed by an explanation of the controller used and the data collected.

A. SETUP OF THE STUDY

In this study a total of 16 able-bodied participants were recruited. Participants had to be at least 18 years old, be fluent in written and spoken English, and have little to no wheelchair driving experience. One of the participants dropped out, while one couldn't complete the study due to severe nausea. Thus, 14 participants took part in the study, 5 of which were allocated for the *control* group, while the remaining 9 were allocated to the *VR* group. The allocation of VR group and control group was random.

Individual participants, from both the test and the control groups, came in for two sessions, on two different dates. In the first session, which was the same for both groups, all participants signed first a consent form and then they were asked to perform a set of driving tasks (described in section 3.2) based on the WSTP on a powered wheelchair and on a real-life course. The wheelchair's joystick (Dx2-REM550/551) was retrofitted with an IMU sensor (the MPU-9250). Completion time and joystick movements were collected for each task. Following the completion of the driving tasks, the participants filled out the WSTP-type questionnaire.

After 2 to 5 days from the first session, according to their availability, the participants came back for the second session. Participants from the control group performed the real-life WSTP tasks and completed the questionnaire again; importantly, this was done to check whether they retained some of the skills learned from the first session. On the other hand, participants from the VR group put on the Polar H10 chest strap, then trained in VR (based on WSTP tasks), and finally they repeated the real-life WSTP tasks as in the first session. During the VR training, the participants were seated on the same wheelchair used in first session, with the motors disabled and using the same joystick (retrofitted with a IMU sensor to control the VR environment). The participants trained in the VR training for as many times as they felt comfortable with (min 1, max 4). Throughout the VR training, heart rate, as well as completion time, and joystick signal were monitored. After the VR training, the participants were asked to complete the Igroup Presence Questionnaire and the Simulator Sickness Questionnaire, and then they re-run the real-life WSTP tasks and completed the WSTP questionnaire.

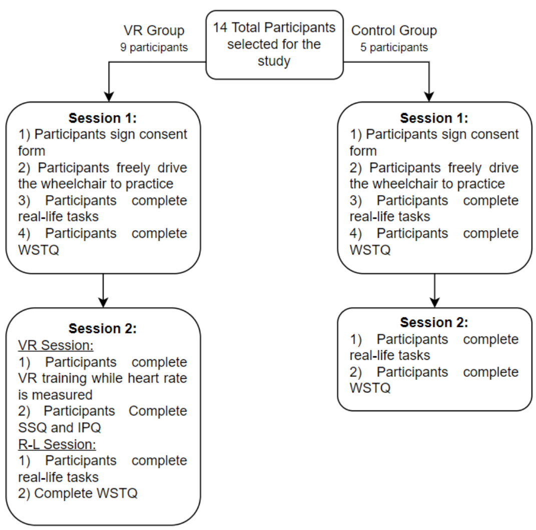

FIGURE 1. **Study setup flowchart.**

B. REAL LIFE SETUP

The real-life set-up, which is used by both groups of participants, in both of their sessions, consists of the participant doing the following tasks: follow a straight line forward for 5 meters and backwards for 5 meters (see Fig. 2c); then, go through a slalom course with 3 obstacles (on a

5m line, 1.5 meters apart, see Fig.2b) both forwards and backwards; finally, go through a maze (with path with alternating width of 1m, 1.5m, 2m, see Fig.2a). The researcher logs the times when the user starts and finishes each task into Unity3D (see Fig. 3). The measures collected when performing these tasks were completion time and IMU signals (the wheelchair's joystick was retrofitted with an IMU sensor to record joystick's movements, see also section 3.4). The participants sit on the wheelchair and use the joystick to drive it at a speed of 1km/h (the lowest speed setting available for safety reasons). Fig. 4 shows a participant completing the real-life tasks.

FIGURE 2. Setup for real life tasks.

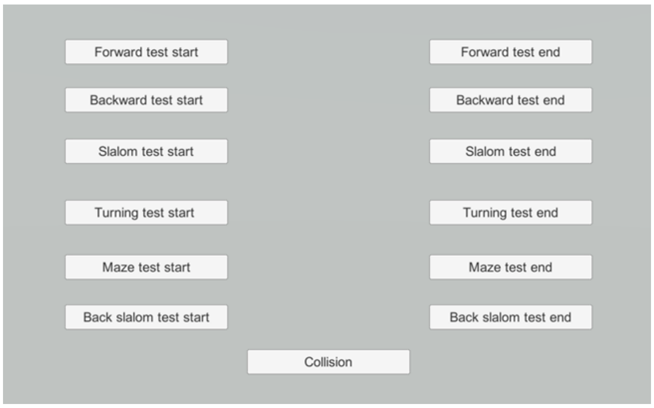

FIGURE 3. Unity3D real-life task log screen.

FIGURE 4. Participant performing real-life task.

C. VIRTUAL ENVIRONMENT

Unity 3D was used to develop the virtual environment, to generate profiles in the form of folders stored locally on the computer's C:// drive for each participant of both groups and to store all the measurements collected during the two sessions of the trials. The environment developed for the VR training is loosely based on the WSTP [22] and the design is a virtual replica of the laboratory room used for the real-life tasks. It consists of five tasks (replicas of the tests conducted in real life): forward driving on a straight line, backward driving on a straight line, forward slalom course, backward slalom course, and a maze (see Fig 5). The VR training was programmed to automatically collect the start and end time of each task, and the accelerometer data of the IMU sensor. The data was saved in the format of an Excel file for each participant. A VR training session consisted in completing all the tasks the participants felt comfortable with in one go. Participants were given the option to train in VR as many times as they felt comfortable in the span of an hour (the minimum time was one and the maximum was four). The reason why participants were given a choice of how many times to trial the system is because each person feels cybersickness to a different extent and thus can use VR for different lengths of time. The system was designed so that while the participant performed the VR training wearing the HMD, the researchers could see the simulation on the Microsoft PC and guide the participant.

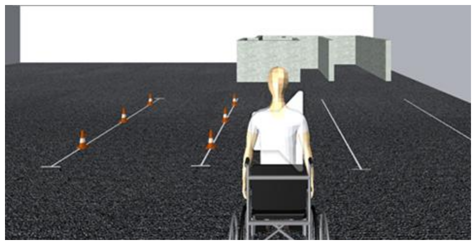

FIGURE 5. VR environment.

D. The VR Controller

A 9-axis IMU sensor (MPU-9250 - connected to a ESP32 microcontroller), retrofitted on the wheelchair joystick (see Fig. 6), is used to control the navigation in the virtual environment. The microcontroller lays on top of a PCB which is battery powered (see Fig. 7), thus making the controller system portable. The values from the accelerometer of the sensor are collected by the microcontroller, to which it communicates with an I2C interface, and sent via a hotspot to Unity 3D (on a Microsoft PC). These values are filtered when used for navigation in VR. As the user moves the joystick, the angle of the sensor changes with respect to the ground, and thus the accelerometer values change. The output of the values has an accuracy of 2 decimal points. We tested the accelerometer to find within what ranges the values fall in the various directions the joystick can be tilted. Thus, when Unity 3D receives the values, it filters them within ranges each corresponding to a different movement command (forward, backward, right and left movements) to control the position of the wheelchair in the VR environment. As the VR controller relies on the IMU sensor, no other signal from the wheelchair is used to control the navigation in the VR environment.

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We also use the accelerometer values to track the movements of the joystick, as a measure of the skills of the participant in driving the wheelchair (in real-life and in the VR sessions). Specifically, we collect the sensor signals to obtain the total length of the joystick movements (see also section 3.5.1) in each task (in real life and in VR).

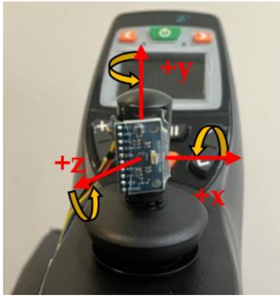

FIGURE 6. **MPU-9250 sensor retrofitted to joystick.**

FIGURE 7. **(a) MPU-9250 sensor retrofitted to joystick and connected to the case (in yellow) containing the ESP32 (b).**

E. COLLECTED DATA

The completion time and length of movement of the joystick are collected using Unity3D, while the heart rate is collected using the Polar Beats App. The WSTP type questionnaire, the SSQ and the IQP questionnaires, are filled out by the user on paper. All this data is stored, organized and plotted with Microsoft Excel; completion time and length of movement of the joystick are processed with MATLAB; the statistical analysis is performed using IBM SPSS.

I. LENGTH OF MOVEMENT OF THE JOYSTICK

The IMU sensor (MPU-9250) is placed on the joystick (see Fig. 6), with its y-axis in the vertical direction. Thus, the horizontal plane in our system, where the rotations of the joystick occur, consists of the z-axis and x-axis of the MPU-9250. The accelerometer values in the x and z directions are recorded for each task, both during the real-life sessions and the VR training, and used to calculate the total length of the movements of the joystick by summing the lengths of each displacement of the joystick in the x-z plane. The length of the movements, L_{jm}, for each task and in each of the two real-life sessions, are collected and compared with each other; paired t-tests are conducted to see if there are any statistical differences within each task. The L_{jm} for each task is also collected and processed during the VR training.

II. COMPLETION TIME

The completion time, C_t, for each task is recorded both in VR and in real life. In VR, the user passes through an invisible collider at the beginning and end of each task, which automatically logs the start and end of each task. In real life, this is manually logged on the real-life Unity interface.

III. WSTP-STYLE QUESTIONNAIRE

A Wheelchair Skills Training Programme (WSTP) type questionnaire was completed by the participants after each real-life session. The original questionnaire has 27 questions [43], but we adapted it to only include questions relevant to the tasks we asked the participants to complete (six questions). This questionnaire allows the participants to do a self-assessment of their driving skills. We statistically compared the results from the first and second real-life sessions using T-tests.

IV. SIMULATOR SICKNESS QUESTIONNAIRE (SSQ)

The Simulator Sickness Questionnaire (SSQ) [24] investigates the cybersickness by asking the user to score 16 symptoms from 0 to 3 (none-0, slight-1, moderate-2, severe-3). This test was administered to the VR group after they completed their VR training. Each of the symptoms corresponds to one or more of three categories: nausea, oculomotor and disorientation. The score for each category (N, O, D) and the total score (TS) were calculated using with the following formulas:

$$N = [a] * 9.54$$
$$O = [b] * 7.58$$
$$D = [c] * 13.92$$
$$TS = ([1] + [2] + [3]) * 3.74$$

Where in bracket, [], the total score of the symptoms in that category is reported.
The simulator sickness questionnaire results were analysed by calculating the average, SD, min and max of each category (N, O, D) and the total score (TS). The scores N, O, D and TS were then compared to reference scores [32] to quantify the level of cybersickness (i.e. none, slight, moderate, severe) caused by our system.

V. IGROUP PRESENCE QUESTIONNAIRE (IPQ)

The Igroup Presence Questionnaire (IPQ) [23] asks the user to assign a score from 0 to 6 to 14 questions. We gave this questionnaire the VR group after their VR training to measure the sense of presence elicited by our virtual environment. Each question falls within one of the following groups: involvement, experienced realism, spatial presence, general presence. We performed statistical analisis on the results from the questionnaire.

VI. HEART RATE

The HR is used as an implicit assessment measure of the participant's physiological state in VR and measured using the Polar H10 sensor with the Pro Strap (as chest strap).

The polar H10 uses ECG sensors, and outputs HR in beats per minute (bpm) at a sampling rate of 1Hz. The technical specifications of the sensor are given in Table 1. The polar H10 sensor was chosen because validation studies in the literature [44] have shown that it offers the best accuracy for the HR measurements compared to other similar sensors. Specifically, the Polar H10 was validated by Schaffarczyk et al. [45] against a 12-channel ECG, where it was found that in terms of R-R intervals and HR the Polar H10 gave similar results to an ECGIt must also be noted that the Polar H10 has been proven to be as accurate as the gold standard ECG Holter device during low and moderate intensity activities [46]. Thus, we deemed the Polar H10 with the Pro Strap (as chest strap) being an appropriate and affordable sensor for our study. Our system aims to be user friendly, therefore we use the Polar Beats app (the recommended app by Polar [47]) to collect the data from the sensor via Bluetooth as a .csv file.

In each VR training task we used the HR data as a proxy of the psychophysical load [20], [21], and correlated it with the performance improvement in real life task. We do this as Bernston et al. [21] believes that type of task and psychophysical load are linked and that this cab be interpreted by changed in HR.

For the statical analysis, a Welch one way ANOVA test is performed to investigate if any statistical difference is present between the HR from different tasks. We perform a Games-Howell post-hoc test to find significant differences between tasks; this is because the HR from different tasks have unequal variance [48]. For all statistical tests we use p = 0.05 as a standard of significance.

TABLE 1
POLAR H10 SPECIFICATIONS [49], [50]

Battery Type	CR 2025
Battery Sealing Ring	O-ring 20.0 x 0.90 Material Silicone
Battery Lifetime	400 h
Sampling Rate	1 Hz
Operating Temperature	-10 °C to +50 °C / 14 °F to 122 °F
Connector Material	ABS, ABS + GF, PC, Stainless steel
Strap Materiak	38% Polyamide, 29% Polyurethane, 20% Elastane, 13% Polyester, Silicone prints

IV. RESULTS

The collected data were processed using MATLAB, and then analysed for statistical testing using IBM SPSS. We propose that the length of joystick movements, L_{jm}, and the completion time, C_t, (for the real-life tasks), can be used as a proxy of the improvement in skills. Paired t-tests were conducted for these two measures from each real-life task, in which the null hypotheses are, respectively:

1) H_0 : (mean-over group of L_{jm} in session 1) - (mean-over group of L_{jm} in session 2)=0
2) H_0 : (mean-over group of C_t in session 1) - (mean-over group of C_t in session 2)=0

While the alternative hypotheses are:

1) H_a : (mean-over group of L_{jm} in session 1) - (mean-over group of L_{jm} in session 2)>0
2) H_a : (mean-over group of C_t in session 1) - (mean-over group of C_t in session 2)>0

Our hypothesis is therefore specific, and so we use a one-sided p-value (with p<0.05) [51], [52] Values of L_{jm} and C_t and the results of the t-tests are reported in the following sections (4.1.1, 4.1.2 – test group, 4.2.1, 4.2.2 – control group).

Regarding the questionnaires, we conducted paired t-tests for the WSTP style questionnaire[43] , while we analyse the SSQ [24] by comparing our scores to reference scores, as done by John et al. [32] , and the IPQ [23]graphically, as done by Achambault et al. [31]. These results are reported in sections 4.1.3, 4.1.4, 4.1.5 (VR group) and 4.2.3 (control group).

For the HR, a one-way Welch ANOVA test with a Games-Howell post-hoc analyses was conducted to measure any difference in HR between tasks.

We present the results for the VR group first and then the ones for the control group. The results are compared and discussed in Section 5.

A. LENGTH OF JOYSTICK MOVEMENT

For the VR group, we measure the length of movement for each participant in a given real-life task, and then we calculate the average for that task across all the participants, $L_{jm\text{-}task}$.. Fig. 9 shows the total $L_{jm\text{-}task}$ for each of the five tasks; the blue bars represent the $L_{jm\text{-}task}$ pre-VR training, while the orange bars represent the $L_{jm\text{-}task}$ post-VR training. A shorter orange bar indicates improvement within that task. This is the case of task 4 (with percentage improvement of 27%); this task has significant difference between pre-VR training and post-VR training (t_8= 2.047, p=0.037). For task 4, on average, the length of post VR training was 134.511 points shorter than pre VR training (95% CI[-17.022, 286.04]).

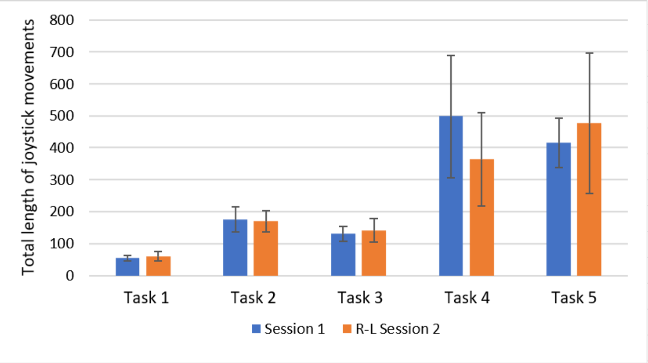

FIGURE 9. VR group total length of joystick movements for each real-life task, before and after VR training (sessions 1 and R-L session 2). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze.

For the control group, we performed the same calculations. Fig. 10, shows the $L_{jm\text{-}task}$ for each of the five tasks. An improvement can be seen in the backwards task (with percentage improvement 26.37%) and the backwards slalom task (with percentage improvement of 16.63%). However, neither task shows significant improvement according to the p-value.

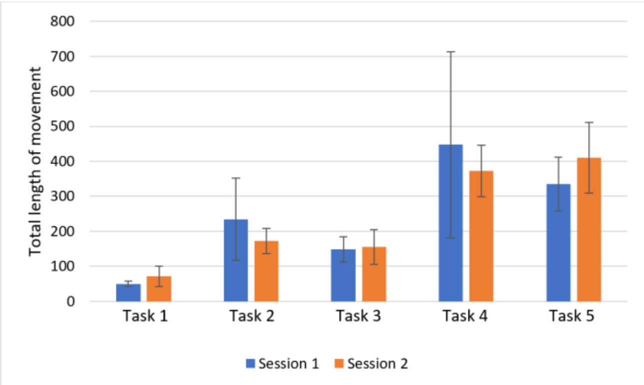

FIGURE 10. Control group total length of joystick movements for each real-life task (sessions 1 and 2, no VR session). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze.

The results of the *p*-values indicate that for task 4 the VR group showed statistically significant improvement in terms of $L_{\text{jm-task}}$, while the control group did not.

B. COMPLETION TIME

For the VR group, we measure the completion time for each participant in a given real-life task, and then we calculate the average for that task across all the participants C_t. Fig. 11, follows a similar pattern as fig. 9. It shows a decrease in C_t for task 4 (with a percentage improvement of 22%). This task has significant difference between pre-VR training and post-VR training (t_8= 2.163, p=0.031). For task 4, on average, the C_t of post VR training was 24.67 seconds shorter than pre VR training (95% CI[-1.63, 50.97]).

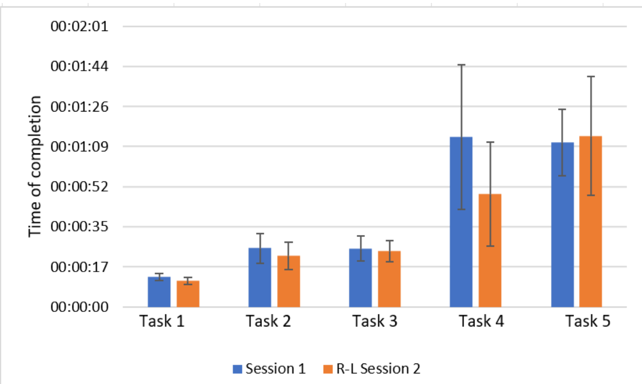

FIGURE 11. Test Group completion time for each real-life task, before and after VR training (session 1 and R-L session 2). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze.

For the control group, we performed the same calculations. Fig. 12, follows a similar pattern as fig. 10. It shows a decrease in C_t for the backwards task (with a percentage improvement of 23.33%) and the backwards slalom task (with a percentage improvement of 13.79%), as well as a slight one for task 5. The t-test show no statistical difference for any of the tasks.

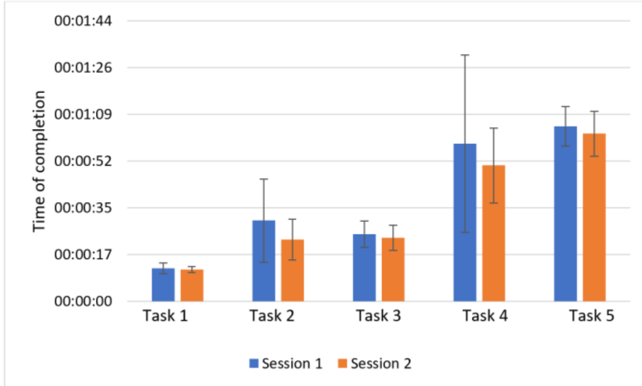

FIGURE 12. Control Group completion time for each real-life task (sessions 1 and 2, no VR session). Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze.

The *p*-values indicate that for task 4 the VR group showed statistically significant improvement in terms of C_t while the control group did not. These results follow the same pattern of the $L_{\text{jm-task}}$ results.

C. IMPROVEMENT IN VR

The real-life task that statistical improvement and in the histogram was the backwards slalom task, thus we looked if improvement also occurred when completing this task in VR. Five participants repeated the VR training more than once, and the average percentage improvement from the first time they did that task in VR to the last is 9.9% for L_{jm} and 9.16% for C_t. This percentage improvement indicates that repetitive training may lead to improvement of skills in VR, which may be associated to real life skills acquisition.

D. WSTP-STYLE QUESTIONNAIRE

We developed our system with the intention of it being accessible and user friendly, therefore importance must be given to the user's subjective perception of it. For the VR group, the perception of improvement was analysed from the answers of the participants to the two WSTQ style questionnaire. We statistically compared the results from the first and second real-life sessions using paired *t*-tests. For the following two questions:

1. Moving the wheelchair forward, for example along a hallway. How confident are you?
2. Moving the wheelchair backward, for example to back away from a table. How confident are you?

the paired *t*-test analysis showed a statistically significant improvement. The analysis reported (t_8=-2.530 , p=0.018) and (t_8=-2.401 , p=0.022) respectively, implying the participant's confidence increased in moving forward and backward.

We also performed t-tests of the WSTQ style questionnaire to the control group, however, no statistical difference is seen. The improvement of the participants' level of

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confidence, shown by the relevant *p*-values, for the VR group, contrasting the lack of improvement for the control group, provides evidence of the effectiveness of our system.

E. SIMULATOR SICKNESS QUESTIONNAIRE

We analysed the level of perceived cybersickness using the SSQ. We compared our results to reference scores calculated as explained in section 3.5.4. The individual symptoms our system provokes are on average *slight*, with the total, TS, being *moderate*. By looking at the min and max, we can see that the scores may be subjective, with participants ranging from not feeling any symptoms to feeling symptoms between moderate and severe. It must be noted that participants took a break between tasks if they felt unwell. Overall, these results demonstrate that our system did not elicit high levels of cybersickness and as such may be used by those with no serious history of cybersickness.

TABLE 2
SSQ RESULTS

	Nausea	Oculomotor	Disorientation	Total
Mean	74.2	53.9	106.7	84.4
SD	41.8	41.6	69.6	49.6
Min	0	0	0	0
Max	133.6	144.0	208.8	175.8

TABLE 3
REFERENCE SSQ SCORES

	Nausea	Oculomotor	Disorientation	Total
None	0	0	0	0
Slight	66.8	53.1	97.4	40.2
Moderate	133.6	106.1	194.9	80.4
Severe	200.3	159.2	292.3	120.5

F. IGROUP PRESENCE QUESTIONNAIRE (IPQ)

We also looked at the IGP questionnaire. The results in table 4 and Fig. 13 show that our system elicits presence as spatial presence with an average score of 4.1, while general presence with an average score of 4.2 (both above the median score of 2.5). However, regarding realism, the scores indicate the participants did not feel that the simulated environment was real. The involvement score was just above the median score, this can be due to the lack of gamification and interactive activities in the simulated environment. The results indicate that although the system gives the users the sense of “being there”, more attention needs to be devoted for the virtual environments in terms of its involvement and the subjective experience of realism.

TABLE 4
IGP RESULTS

	Mean	SD
Involvement	2.93	2.08
Experienced Realism	1.93	1.86
Spatial Presence	4.1	1.63
General Presence	4.2	1.33

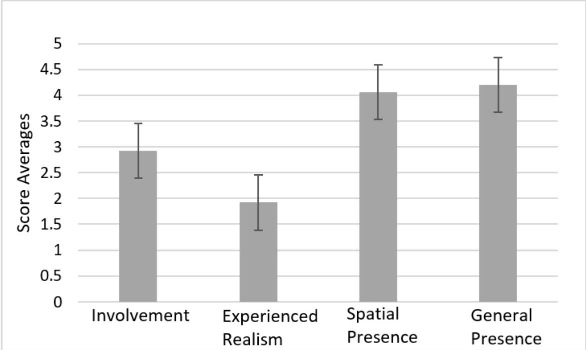

FIGURE 13. Average Igroup Presence Questionnaire results.

G. HEART RATE

As mentioned already, a Welch one way ANOVA test has been performed to investigate if any statistical difference is present between the HR from different tasks. There was a statistically significant difference in HR between tasks ($F(5,9169) = 206.385$, $p = <0.001$).

Given that the results from sections 4.1 and 4.2 have reported the biggest improvement in task 4, a Games-Howell post hoc test between task 4 and each of the other tasks was performed. This revealed a statistical difference the level 0.05 in HR between task 4 and every other task at. Fig. 14 represents a Box and Whisker plot of the HR data of all particiants grouped by task, while table 5 lists all the tasks with the corresponding mean HR, standard deviation and standard error. We see an increase in mean, median and minimum HR values for the backward slalom task, which may suggest that task 4 is the task with a higher psychophysical load. During this task, it was noticed that some participants looked back to avoid the obstacles, as they would have done in real life, thus indicating higher involvement in said task. This result also correlates to what was found in sections *IV A* and *IV B*, where *p*-values for $L_{\text{jm-task}}$ and C_t show statistical improvement in skills after VR training for task 4 but not for other tasks. This finding may indicate a relationship between higher involvement in a task and acquisition of skills to perform more efficiently said task.

TABLE 5
HEART RATE FOR VR SESSIONS

	Mean	SD	Std. Error
Forward Task	75.39	9.05	.45
Backward Task	76.97	10.04	.38
Forward Slalom Task	78.30	7.90	.23
Backward Slalom Task	79.27	9.04	.25
Maze Task	75.95	8.86	.17

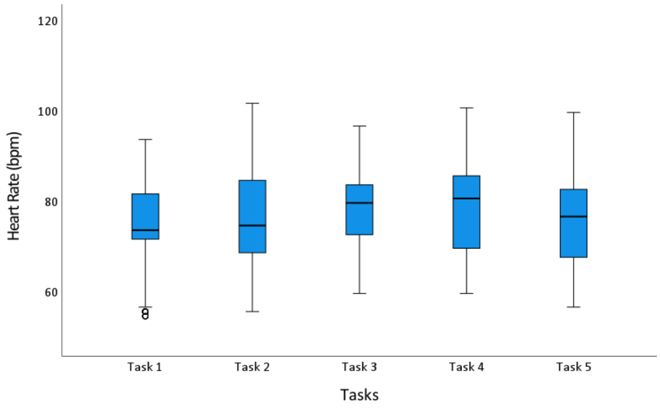

FIGURE 14. Box and Whisker Plot for the HR. Figure legend: task 1-forward, task 2-backward, task 3-slalom, task 4-backward slalom, task 5-maze.

V. DISCUSSION

In our study we hypothesised that VR training can help WUs to improve their driving skills. Our results show that this was the case, specifically for the backward slalom task, in which the length of movements, $L_{jm,}$ and completion time, $C_{t,}$ improved by 27% and 22% respectively, between the real-life sessions 1 and 2 done by the VR group. Further, the highest improvement of an individual participant was 58% (L_{jm}). It must be pointed out that the statistical tests on the control-goup results, indicate that there is no significant improvement on average between real-life sessions 1 and 2, when no VR training is undertaken. However, the variance of our results was large and limited participants took part in the study, thus bigger trials should be conducted in the future.

Comparing a user's performance in real life before and after VR training is essential to see if a person has indeed acquired any skills wih VR, yet this is not often done [14]. In our study, the backwards slalom task is where the participants improved the most. This was perhaps the most difficult task for the participants to do as it required the most maneuvers to complete (see Fig. 9 and Fig. 10). This is also evidenced by the HR results, which show that participants had the highest HR values while performing the VR backwards slalom task (see Fig. 14 and table 5). This may suggest that VR is more beneficial for more challenging tasks, at least in immediate to short term acquisition of skills.

Similar to our results that show the HR increases in more difficult tasks, Bassano et al. [53] found a slightly elevated HR in faster tasks in ship-handling simulations, which they believed to be related to the difficulty of the tasks. Furthermore, according to Bertson et al. [20], [21], the relationship between changes of HR based on tasks may be due to the different psychophysiological loads of tasks. Therefore, HR data may suggest the type of tasks that may need to be looked at for better training for a specific participant.

We intended to demonstrate also that affordable technology can be used within a VR training system which leads to improvement of driving skills in real life. We use an IMU sensor simply attached to a powered wheelchair joystick to control the navigation in VR. The same sensor is also used to record the L_{jm} in real life session to measure skill's improvement. Using an IMU sensor attached to the joystick, would enable the user to remain seated on their own wheelchair and use their own joystick to conduct their training in VR, without 'hacking' into the electronics of the joystick.

In our study we assumed that the more proficient in driving a person becomes, the fewer maneuvers they will require to achieve a task. In this regard, Sorrento et al. [41] compared joystick movements and strategies between novice wheelchair users and expert ones and found that in more difficult tasks the expert group required less joystick maneuvers than the novice ones. We justify the reliability of using length of movements as a measure of improvement, by looking at its relationship with a commonly used measure, namely completion time (C_t) [11], [14]. We noticed that the results of the L_{jm} show a similar pattern with the C_t ones for both the VR group and the control group analysis. Similar findings were reported by Archambault et al. [31].

Our participants were also asked to fill out an adjusted version of the WSTP questionnaire after each of the two real-life sessions, to see if they perceived they had improved their skills. We compared the results for both the control group and the VR group using paired *t*-tests. Though paired *t*-tests are best suited for continuous data points, rather than discrete ones like the questionnaire, due to the limited number of participants we believe this to be the most appropriate statistical test [54]. The results of this analysis indicate the VR group perceived improvement with tasks 1 and 2 (forward and backward), while the control group did not.

To assess the presence and realism elicited by our system, we asked users to complete the IPQ. The results demonstrate that our system elicits presence, with above average scores (see Fig. 13). This is important as high levels of presence are related to VR based learning effectiveness [18]. However, realism and involvement were not highly elicited. This may be due to the lack of gamification and engaging tasks in our VR environment.

As one of the limitations of VR is cybersickness, we also performed the SSQ. Our results show that our system induces on average slight sickness. By looking at the minimum and maximum scores given by our participants, we can see that cybersickness is very subjective, with participants ranging from not feeling anything, to feeling symptoms between moderate and severe (see table 2). As cybersickness occurs due to the conflict between the visual stimuli and missing vestibular stimuli [55], when using VR it will be present to some extent, in fact 40-70% of users are prone to experience it after 15 minutes [55]. To limit this effect, other methods for virtual training have been used such as a desktop monitor; however, studies comparing

HMDs and monitors found that HMDs was more effective in teaching wheelchair skills than a desktop monitor [32].

VI. CONCLUSION AND FUTURE WORK

In this study we aim to address the affordability and accessibility of powered wheelchair skills training using VR, and the standardisation of these trainings. We use low-cost equipment to develop a controller that can be retrofitted to the wheelchair user's joystick, which can be easily adapted to different chairs. The VR headset in our study can be used as a standalone device, allowing the user to remain seated in the comfort of their own chair while undergoing the training.

Currently, there is a heterogeneity of approaches to VR training, hence with our work we propose a protocol that could be used to standardise these trainings. We based our method on the renowned WSTP which has been validated for real-life training. We suggest using adapted WSTP tasks in VR and conducting the same real-life tests before and after VR training to see if the VR training leads to acquisition of skills. To our knowledge, the testing of skills before and after VR training is not often done though it is believed to be needed [14]. Our system is designed so that the signal/data from the IMU sensor (retrofitted on the wheelchair joystick) can be used to validate the acquisition of skills in real life, without requiring further equipment.

The results of our study support our two hypotheses: 1) acquisition of wheelchair driving skills can be accelerated using VR; in fact, we showed that our VR training system supports the immediate to short-term acquisition of skills for more challenging tasks (p=0.037 for $L_{\text{jm-task}}$ and p=0.031 for C_t) post VR training for our hardest task; 2) affordable technology can be used to train in VR driving skills which are transferable to real life. Those results also corroborate our standardisation protocol as a way to train and assess wheelchair driving skills. Furthermore, our system does not elicit high levels of cybersickness, and evokes a sense of presence which has been shown to be related to the effectiveness of VR based learning.

We believe our results to be insightful in the research field as they demonstrate that affordable and accessible VR for wheelchair skills training can be effective and safe to use. Furthermore, our proposed protocol for the VR training, based on the renowned WSTP, enables the training to be standardised, which, we believe, may increase its reliability and popularity, as it has done for real life programs.

Nonetheless, our study has some limitations that we hope to address in our future work. Our study shows that VR aids with the acquisition of short-term retention of skills, even with only one session; still, more sessions, spread further apart, should be conducted to determine the effectiveness of our system for long-term retention of skills. Furthermore, the system needs to be tested with more participants, with different wheelchairs and with the target population (e.g., new wheelchair users). Although overall our system did not elicit high levels of cybersickness, ways to reduce it further should be investigated so that the system can be used by a wider audience. We also intend to increase participants' engagement in future work, to make the training more enjoyable and in turn more effective. Moreover, as we found that more difficult tasks have the highest improvement and elicit the highest psychophysical load (as evidenced by our HR measurements), future work will focus on more challenging tasks (e.g., outdoor driving tasks) with elements of gamification to stimulate involvement.

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