Entertainment Computing 34 (2020) 100352

Contents lists available at ScienceDirect

Entertainment Computing

journal homepage: www.elsevier.com/locate/entcom

Evaluating the user experience of omnidirectional VR walking simulators

Kyle Hooks[a], Wesley Ferguson[a], Pedro Morillo[b,*], Carolina Cruz-Neira[a]

[a] Emerging Analytics Center (EAC), University of Arkansas at Little Rock (UALR), Little Rock, AR 72204 USA
[b] Computer Science Department, University of Valencia, 46980 Paterna, Valencia, Spain

ARTICLE INFO

Keywords:
Comparative study
HCI – Human Computer Interaction
High immersive environments
User interfaces
Virtual reality
VR platforms
Omnidirectional treadmills

ABSTRACT

Omnidirectional treadmills (ODTs) have been traditionally proposed as a promising solution for users' navigation in large-scale virtual environments. These mechanical devices enable users to perform locomotive motion with 360-deg freedom, while keeping their position fixed in the physical world. However, most locomotion approaches based on omnidirectional treadmills have presented either high acquisition or maintenance costs, being the capabilities of the general public, or a limited reliability. In this paper, we present a comparative usability and acceptance study with real users evaluating the two most common approaches for the development of this type of Virtual Reality (VR) walking simulators, whether flat-based or bowl-based omnidirectional treadmills. The results of our study indicate that both design alternatives accomplish a similar performance and can be considered as personal, low-cost walking simulators for navigation in virtual environments. Nevertheless, when compared between themselves, the users preferred the bowl-based omnidirectional VR treadmill when following three different selection criteria: overall preference, recommendation, and usefulness. Last, a correlation analysis showed statically significant correspondences among the parameters concerning to the simulation presence, which in turn, are related to the global scores and responses given by the participants of the Virtual Reality experiment.

1. Introduction

Users' navigation in virtual environments is a fundamental challenge that has been widely addressed in the scientific community [1]. Among other alternatives, the omnidirectional treadmill (denoted as ODT) has been considered as one of the most promising solutions for allowing users to walk or even run in virtual environments [2]. Fundamentally, these devices enable users to move around with 360-deg freedom while keeping their position fixed in the physical world, simulating an infinite ground for walking in any direction [3]. This near-natural walking is usually achieved by a basic mechanism consisting of on a continuous conveyor or a static sliding surface where the users walk, usually supported by a body harness. Since most body harness or standstill devices allow the user to physically rotate through a full 360 degrees, omnidirectional treadmills can generate motion in any direction [4]. Although some commercial omnidirectional treadmills have been released as potential to generate the feeling of walking, most of the products have lacked an affordable, intuitive, and ergonomic VR walking experience [5].

However, some low-cost ODTs have recently broken into the market of omnidirectional treadmills for Virtual Reality purposes [6–10]. These devices, supported by crowdfunding projects, promise to be reliable and open solutions, which allow the users to move naturally within the virtual environments. These solutions share a similar visual aspect, but they have been developed following different mechanical principles to allow user's feet slide across the floor of the treadmill [9]. Concretely, some recent omnidirectional treadmills incorporate flat floors, where the users walk on [8,11,12], while another solutions use concave surfaces to facilitate the walking simulation to the user [7,10].

In this paper, we present a comparative study of the flat-based and bowl-based omnidirectional treadmills, denoted also as FODT or BODT, using two well-known commercial products as representatives of both design alternatives. The comparative study was based on a counter-balanced measures design [13], which allows determining whether using one of the two alternatives first has some effect on the scores for the another system, given that flat-based and bowl-based omnidirectional treadmills are common and not exclusive solutions when users walk in virtual environments. To the best of our knowledge, neither technical arguments have been published to support which of the mechanical principles for the development of omnidirectional treadmills seems more effective, nor have studies been published assessing and comparing these types of VR devices with real users.

For this reason, our primary hypothesis was that there would be significant differences between the performances of both

* Corresponding author.
E-mail addresses: kdhooks@ualr.edu (K. Hooks), wrferguson@ualr.edu (W. Ferguson), Pedro.Morillo@uv.es (P. Morillo), cxcruz@ualr.edu (C. Cruz-Neira).

https://doi.org/10.1016/j.entcom.2020.100352
Received 5 September 2019; Received in revised form 27 December 2019; Accepted 5 February 2020
Available online 14 February 2020
1875-9521/

omnidirectional treadmills evaluated. Moreover, our secondary hypothesis was that participants would prefer the representative of the bowl-based omnidirectional treadmills (since this design alternative seems to allow a simpler sliding on the walking surface apparently) and this drove the design of the users' preference analysis.

The rest of the paper is organized as follows: Section 2 reviews the related work in the area of locomotion systems and omnidirectional treadmills for the simulation of the movement in Virtual Reality. Section 3 presents the material and methods involved in our comparative study. Next, Section 4 describes the performed study and Section 5 presents the results of the statistical analysis obtained from the experiments conducted with real users. Finally, Section 6 summarizes the conclusions of the research and the future work coming out of our results.

2. Related work

One of the longest-standing problems for the field of Virtual Reality has been addressing how users move throughout the virtual environment. Different methods have been proposed and implemented that utilize the user's gaze and/or hand gestures, virtual, and physical controls for movement [1,5]. Of these three, virtual controls tend to be the most flexible option, where users can interact with virtual controllers, handles, and wheels in order to move about the virtual environment. However, virtual controls lack haptic feedback, and can prove difficult for users to interact with [1]. Hand gestures and gaze-directed flying are simpler methods of free movement in the environment, and can be more intuitive than virtual controls to use. Still, flying in virtual environments often poses a problem in terms of confusion and disorientation for newer users. Physical controls tend to be the least flexible compared to the previous methods, but can be well-suited to specific situations, such as steering devices and pedals used for driving simulators [14]. Nonetheless, natural mapping between physical controls like knobs, joysticks, and trackballs and the interactions they enable in the virtual environment are generally lacking.

Head and body tracking systems have been developed to allow for natural movement, but are limited to the physical space in which they are set up. Omnidirectional treadmills stand as an alternate physical control for locomotion in virtual environments [2], allowing for a more natural means of moving in VR without concern for navigational space limitations. These VR devices have been classified as active or passive solutions [15]. Active omnidirectional treadmills include a system of actuators (normally electromechanical), which keep the user within the limits of the walking surface. In passive approaches, a physical element (usually a harness) prevents the user from moving completely. Although the heavy first passive treadmills oriented to Virtual Reality purposes were replaced by active solutions [16], due a more realistic walking sensation, new lighter and low-cost passive products are widely available and common in the market of omnidirectional treadmills for Virtual Reality.

KatWalk is an omnidirectional treadmill that supports actions such as crouching, jumping, sitting, as well as forward and backward movement on a flat, static surface [7]. This bowl-based ODT detects direction by a hanging harness and movement through sensors worn on the feet. KatWalk's advantages lie in its ring-less and nearly strapless design, intended to free the user of limitations common to omnidirectional treadmills. With this design, users are able to move naturally and without any physical limitations save for the single harness around them. Its disadvantages are its moderate height and floorspace requirements, as well as the necessity for special shoes so that users can adequately use the system.

Unlike the stationary surface of the KatWalk, a flat-based omnidirectional treadmill named Spacewalker VR [9] utilizes a normal rolling treadmill surface in tandem with pressure sensors to detect foot movements. Spacewalker's biggest disadvantage compared to other omnidirectional treadmills comes from how it orients its users. The rotation of the user is adjusted by the yaw of the user's head, effectively negating normal decoupling of their independent head and body movements with VR headsets. Still, this method of orientation provides the user constant access to a set of knobs on the ring around their waist without having to constantly turn around. A different flat-based ODT approach is proposed by Wizdish in ROVR [8], where walking is simulated through continuous sliding on a static and flat surface in which the user is not provided with harnesses.

Finally, a significantly large device is the Infinadeck [12], which uses a real treadmill capable of providing movement in two directions. The walking surface is one large belt, covered in smaller belts that move perpendicular to the first. The walking surface is larger than flat-based omnidirectional treadmills previously described, and has a minimal harness setup much like KatWalk. Disadvantages for Infinadeck include very large space requirements, large weight requiring more robust than normal construction, and a high estimated buying price and maintenance costs, which are prohibitive to normal consumers and smaller research groups. While analysis of individual treadmills as a locomotion system exist [6], studies comparing user experience with different flat-based and bowl-based omnidirectional treadmills commercially available devices have yet to be pursued. Many omnidirectional treadmills available today, including the Virtuix Omni and Cyberith Virtualizer used in our experimental study, use similar methods of tracking and locomotion as their predecessors, such as rolling and/or static surfaces, motion sensors, and harnesses. However, what differentiates these systems are the unique implementations and arrangements of their common components.

3. Method

For our study, we have selected Cyberith Virtualizer and the Virtuix Omni as representatives of flat-based and bowl-based omnidirectional treadmills, respectively. The reason for this selection is that both passive and low-cost products, which have recently broken into the market of omnidirectional treadmills for Virtual Reality, include a very similar solution to fasten the user, but incorporate the basic elements behind both design paradigms (flat-based vs. bowl-based ODT) to simulate the feeling of walking. Also, we developed a Virtual Reality application with two separate scenes for both the flat-based and bowl-based treadmills. The environment in the application was arranged in a maze-like layout for the purpose of observing users' experience navigating a complex environment with each of the omnidirectional treadmills. Assets from Unity's Stealth tutorial were utilized and adjusted to create the scene and immerse the user in the tasks given in the study [17].

3.1. VR system

For our study, two identical computer stations were used for testing with each of the flat-based and the bowl-based treadmills. These stations were kept in separate rooms to allow for simultaneous testing of members from two different groups of participants, without exposing one to the other during testing. During the experiment, a logging script recorded data regarding the user's position, collisions with walls/objects and time spent in the virtual environment. The user's head position and rotation were recorded in three dimensions and in a four dimensional quaternion, respectively. The data recording script wrote a new set of positional, rotational, and timed values multiple times per second, with an asynchronous write when the user completed the long-distance virtual walks.

In the scenes for both treadmills, users were presented two tasks to complete, denoted as TASK1 and TASK2. Users have to complete some goals for what they will walk a distance in the virtual environment. The number of goals to be completed has been selected intentionally different in both tasks to recreate two different experimental setups. In TASK1, the user was instructed to navigate to the location of a bus near the center of the environment, designated by a large, yellow sphere

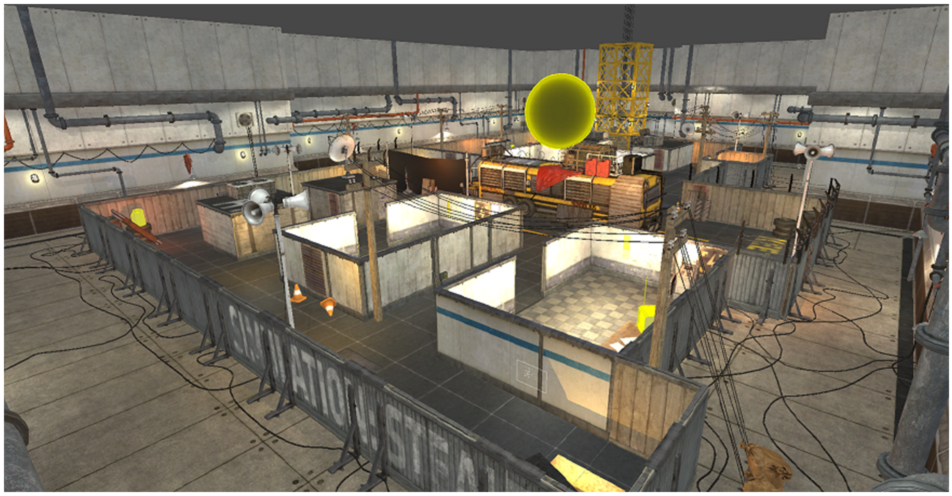

Fig. 1. An overhead view of the virtual environment, showing the goal for task one. The user's starting location is marked by a red dot.

with the user starting at one corner of the environment (Fig. 1). The sphere was deliberately placed high enough in the scene to be seen by the user from the beginning of the scenario, as well as from virtually anywhere in the environment. Before the user started TASK1, text filled the screen explaining what the user needed to accomplish, which was get to the yellow sphere. The users were instructed to read these directions out loud to ensure they understood what to do. Once the user indicated they were ready to begin, a script was enabled that recorded their head position and rotation, as well as how long it took for them to navigate from their starting location to the sphere. Once the user navigated to the sphere, the script stopped recording data and the user was told to stop. Additionally, the data recording script was paused after completing TASK1 until starting TASK2 so there was no erroneous data while waiting between both tasks.

In TASK2 the participants were instructed to explore the environment and obtain four objects in the environment in order: a bag of rations, a crate of munitions, a TV set, and a gasoline can. These objects were distributed across the environment, and the next object the user needed to retrieve was highlighted in the same manner as the sphere (Fig. 2).

After retrieving the objects, the user would return to the same location by the bus they were at when starting the second task. As in the first task, when the user was ready to begin, a script was enabled that recorded the user's head position, rotation, number of occurred collisions and overall time for task completion. Additionally, as in TASK1, the user needed to read text out loud that explained the goals in TASK2, which were exploring the environment to collect different objects and returning to the bus afterward.

3.2. Hardware and software

An Oculus Rift CV1 headset was used to visualize the virtual environment for participants [18]. Oculus Rift, as well as HTC Vive [19], are considered industry leaders for the development of high immersive applications, while cheap head-mounted display (HMD) models, and are widely available and affordable in the market of Virtual Reality devices. The display of the Oculus Rift CV1 consists of two 90-mm. screens, with a combined resolution of 1080 × 1200 pixels per eye and a refresh rate of 90 Hz [18].

The two computers that ran this experiment have the same technical hardware in order to guarantee a fair comparison between the two experiment environments. Both use an Intel® Core™ i7-4790 CPU @ 3.6 GHz, 16 GB of RAM, and an NVidia GeForce GTX 970 graphics card. The framerate within the Oculus Rift CV1 displays was satisfactory and consistent between 70 and 80 frames per second (FPS) for the two treadmills.

This experiment examined two particular flat-based and bowl-based omnidirectional treadmills: the Cyberith Virtualizer and the Virtuix

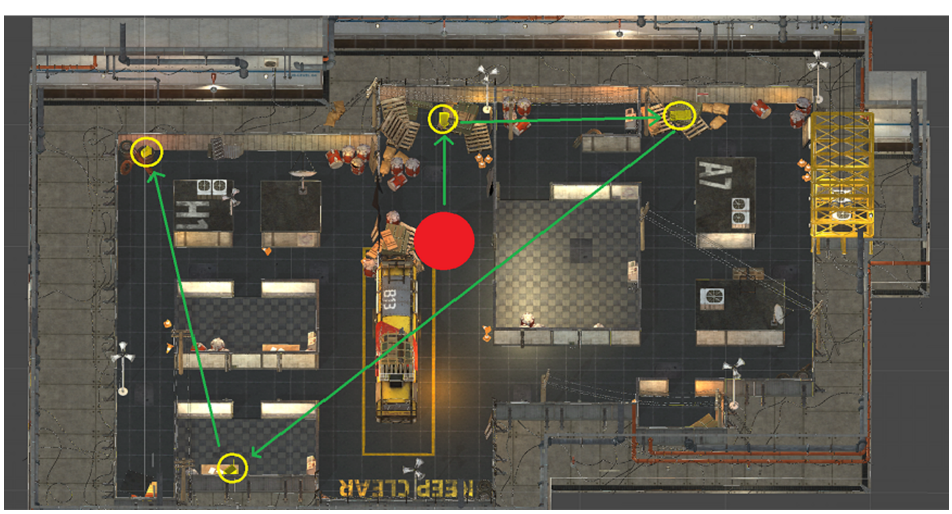

Fig. 2. A view of the objects users to be obtained in the environment. The order in which the user navigated to the objects is marked by yellow arrows, starting at the bus.

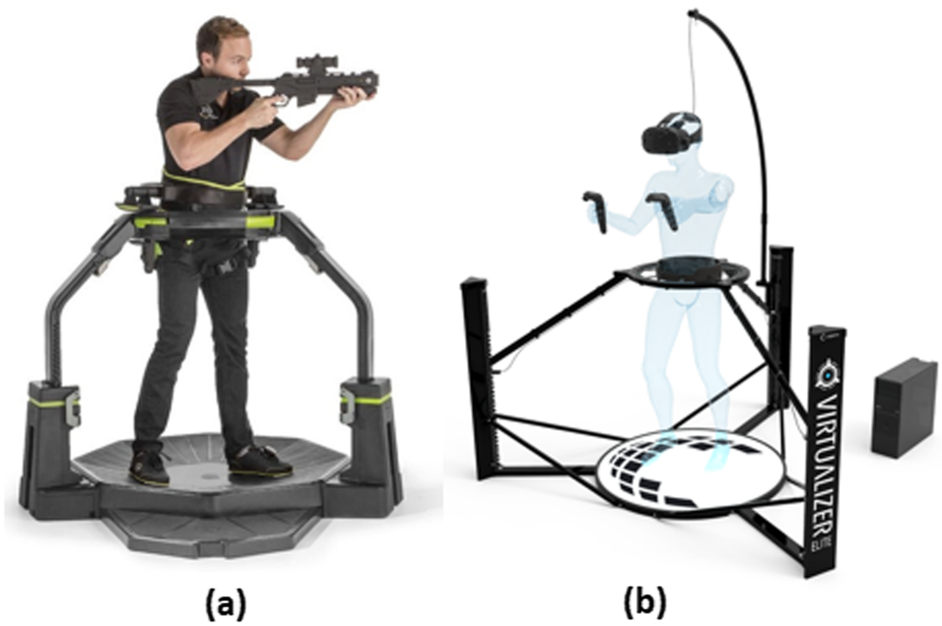

Fig. 3. The BODT-Virtuix Omni (a) and the FODT-Cyberith Virtualizer VR (b) platforms.

Omni. Both omnidirectional treadmills feature low-friction walking surfaces, free-rotating harnesses, and adjustable heights for their supporting rings, but have notable differences in their methods of movement and movement tracking.

The Omni (Fig. 3a) features a bowl-shaped walking surface to emulate a user's natural stride with little resistance. Using Virtuix's included software, the user's movements are tracked by two accelerometers attached to their ankles. The Omni's harness slides freely about the supporting ring, allowing the user to turn in any direction without restraint. Magnetic sensors in the supporting ring also track the user's orientation and can detect both forward and backward walking based on which direction the user is leaning. The height of the supporting can be adjusted to suit the user, but due to the locks' placement at the base of the treadmill, must be performed either outside of the ring itself or with the aid of another person.

The Virtualizer (Fig. 3b) has a flat walking surface as its base, intended to feel the same to users as walking on level ground. Six optical sensors in the base plate of the Virtualizer detect movement across it and return a raw, signed speed value. The harness of the Virtualizer is fixed to the supporting ring, but rotates smoothly using steel ball bearings. By using the movement of these bearings around the harness, the user's orientation is determined relative to a fixed point on the ring, which can be re-calibrated using Cyberith's provided software or SDK. Unlike the Omni, the Virtualizer also features a curved vertical bar for suspending headset cables away from the user's body. Additionally, the height of the supporting ring can be adjusted while on the treadmill via a handle on the supporting ring near the waist.

The most notable difference between both devices is located in the floors of the treadmills. As an example of a bowl-based treadmill, the Virtuix Omni (Fig. 4a) has a slight incline near the edges of the floor, similar to that of a bowl, while the Cyberith Virtualizer (Fig. 4b), as an example of flat-based treadmill, has a horizontal floor to walk on. Moreover, the floor of the Cyberith Virtualizer includes 6 optical trackers, which determine both the angle of direction and the speed of the user' feet. These sensors pick-up the horizontal position and avoid attaching any other device to the user' legs.

Both of the scenes used in the experiment were created using Unity, specifically '*version 5.4.5f1*'. Unity is a free-to-use cross-platform game engine developed by the company of the same name [17]. The scenes used for each treadmill were visually and functionally equivalent, with the only differences being assets and scripts used to manage user input. A ".unitypackage" file containing the Virtualizer's respective assets was obtained from Cyberith's developer website, while version 1.7.1 for the Omni's Unity SDK was obtained from Virtuix's developer website. The scripts for recording the user's head position and rotation, as well as the user's time for both tasks, were written in C#.

4. Study

The goal of this comparative study is to determine if there are significant differences in the performance and the user's level of satisfaction between the existing two main paradigms for the design of VR treadmills, which are currently available to the general public. To fulfill this goal, the two groups of adult participants (denoted as Group A and Group B), equipped with an Oculus Rift HMD, were introduced in an immersive labyrinth virtual environment where they had to locate a set of objects located within the scene. The first group initially used the bowl-based omnidirectional treadmill (Virtuix Omni) as a locomotion device in the virtual environment, while the other group initially used the flat-based omnidirectional treadmill (Cyberith Virtualizer).

4.1. Participants and measurements

The experiments were given in the summer of 2018 in the Virtual Reality laboratory of the Emerging Analytics Center at the University of Arkansas at Little Rock (UALR) with 54 participants (43 men and 11 women) to guarantee statistically significant results [20–22]. The participants included students, faculty and administrative staff of this university. All of them, aged between 18 and 56 years old (23.74 ± 7.99), were provided informed consent before taking part in the study. Fig. 5 shows different participants during the experiments using both VR treadmills evaluated.

The results have been obtained based on empirical measures and questionnaires from the participants in the experiments. Concretely, two questionnaires have been used along the experiment. The first questionnaire was initially filled by our staff including the number of occurred collisions and the time to complete the two virtual tasks described in Section 4.1. Next, the participants completed 36 questions on a 1–7 Likert scale (1 = strongly disagree, 7 = strongly agree) related to their perception about interaction, 3D sensations and satisfactions, after testing a given VR treadmill.

Although the total content of the questionnaire is not shown here for

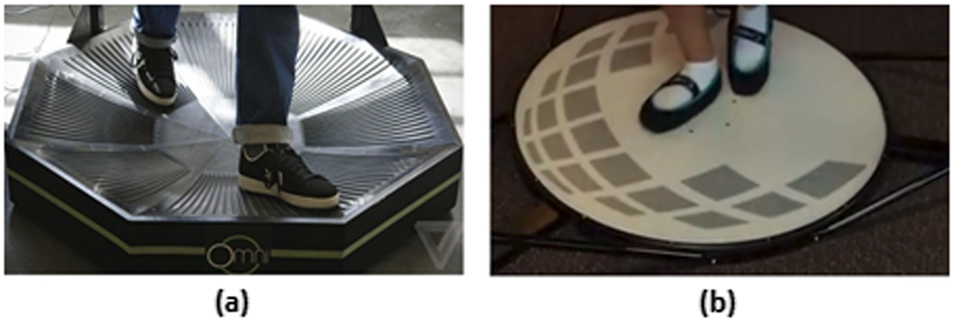

Fig. 4. Differences of the floor provided by the BODT-Virtuix Omni (a) and the FODT-Cyberith Virtualizer VR (b) platforms.

the sake of brevity, most of the questions were adapted from the presence questionnaires proposed by [23] and [24]. Since the sense of presence is highly correlated with the degree of perception of that environment [25], we have designed these questions in order to measure that sense of presence. The 36 questions are grouped according to six presence factors [23]. In our experiments four questions were related to control factors (degree of control, responsiveness, anticipation of events and mode of control), four questions related to sensory factors (sensory modality, environmental richness, multimodal presentation and consistency of multimodal information) three questions related to distraction factors (selective attention and interface awareness) and ten questions related to realism factors (scene realism, information consistent with objective world, meaningfulness of experience, among others). We also added nine questions related to ergonomic factors (device comfort, effort, and fatigue, among others) and six other questions relevant for the experiment (product adequacy, engagement, learning curve, among others).

Different variables were created to condense the 36 questions by Likert responses of the item for a particular subscale together. Hence, the variables CF, SF, DF, RF, EF and OF represent the dataset from the responses to the control, sensory, distraction, realism, ergonomic and other factors, respectively.

After responding to these questions on a 1–7 Likert scale (1 = poor, 7 = excellent) participants scored three different aspects related to the immersion level, the final product, and the usefulness as a locomotion system for a given VR treadmill. The responses to these questions were expressed into the datasets denoted as 3D, SCORE and UNESS.

Moreover, information regarding to gender, profession, educational background, and age data from the participants was also collected in this questionnaire.

The second questionnaire contains the same content as the first questionnaire, as well as three questions where participants select one of the two VR treadmills following three different criteria: personal preference, recommended product and most useful solution as a walking device in a VR environment. These responses were condensed into the datasets labeled as LIKE, RECO and USEFUL, respectively. Moreover, the participants could express their opinions and justifications to their responses for the three selection criteria.

4.2. Procedure

All the participants were randomly assigned to one of two groups, identified by the VR treadmill they tested first. By the end of the experiment, all the participants tested both treadmills. Fig. 6 shows the procedure followed where participants belonging to Group A tested the bowl-based omnidirectional treadmill (Virtuix Omni) first, and experienced the flat-based omnidirectional treadmill (Cyberith Virtualizer) afterwards. By contrast, users in Group B were required to test the Cyberith Virtualizer first and next the Virtuix Omni treadmill. In our experiments, the rest time between each comparison trial for a given user was about 10–15 min.

The protocol followed with the participants starting with a presentation of the entire experiment and a 10-minute verbal training session for both treadmills. Then, the participants use the first treadmill and complete TASK1 and TASK2 within the immersive virtual environment. Meanwhile, our staff monitored the users' actions, the number of occurred collisions and the captured the time to complete both tasks, denoted as COLL1/COLL2 and TIME1/TIME2 in Fig. 6. After completing this virtual experience, participants fill the first questionnaire. Next, all participants use the other VR treadmill, complete the tasks and fill the second questionnaire.

5. Results

This section presents the statistical analysis of the sets of data obtained from the experiments conducted with real users. All the acquired

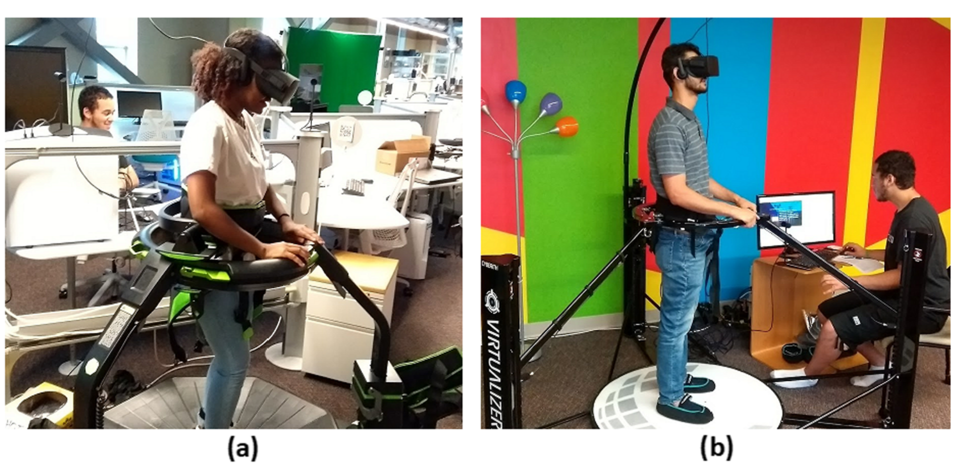

Fig. 5. Participants during the experimental session testing the BODT-Virtuix Omni (a) and FODT-Cyberith Virtualizer VR (b) platforms.

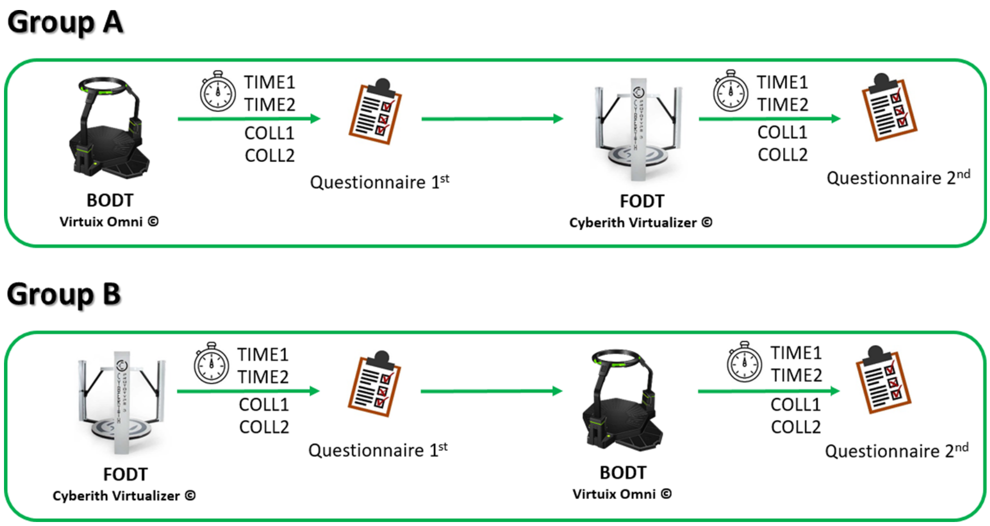

Fig. 6. Procedure followed in the comparative study.

datasets related to the study variables follow a normal distribution. Therefore, parametric tests, such as the *t*-test and the Cohens test for paired and unpaired data were used for analyzing the relationship among the different parameters involved in the experiment. As an example, the Kolmogorov–Smirnov test (D = 0.2321 and p-value = 0.4102), Anderson-Darling test (A = 0.5139 and p-value = 0.2511) and the Shapiro-Wilk test (W = 0.6332 and p-value = 0.1740) confirmed that the sensory factor variable (included in the dataset denoted as SE) follows a normal distribution. In addition to the parametric tests, Cohen's d-index and eta-squared are provided as a measure of effect size. Moreover, some interesting statistical significance effects were obtained completing an analysis of variance (ANOVA) with post-hoc comparisons by Tukey's tests and Bonferroni's tests.

Table 1 shows the average and the standard deviation of the time needed by the participants to complete the two tasks (denoted as TIME1 and TIME2), as well as the results obtained with the first questionnaire

Table 1
Averages and standard deviations for independent groups that tested Virtuix Omni (Group A, first row for each parameter) or Cyberith Virtualizer (Group B, second row for each parameter) first. The responses to the questionnaires were grouped into the SF (sensory), EF (ergonomic), RF (realism), CF (control), DF (distraction) and OF (other) parameters, representing the presence factor.

Parameter	AVG ± STD (s.)	t	p	d.f.	Cohen's d
TIME1	57.07 ± 32.05	−2.63	0.011	52	−0.728
	77.53 ± 24.18				
TIME2	358.61 ± 238.30	−0.81	0.422	51	−0.235
	402.24 ± 133.36				
SF	6.14 ± 0.68	0.347	0.730	52	0.095
	6.07 ± 0.85				
EF	5.50 ± 0.90	2.759	0.008	52	0.753
	4.74 ± 1.12				
RF	5.73 ± 0.63	2.180	0.134	52	0.600
	5.27 ± 0.92				
CF	4.75 ± 1.23	3.111	0.003	52	0.848
	3.71 ± 1.22				
DF	5.21 ± 1.35	1.251	0.216	52	0.341
	4.75 ± 1.42				
OF	6.25 ± 0.62	2.857	0.006	52	0.780
	5.71 ± 0.78				
3D	6.37 ± 0.63	2.322	0.124	50	0.667
	5.76 ± 1.20				
SCORE	5.36 ± 1.25	3.903	0.001	51	1.074
	3.84 ± 1.58				
UNESS	5.43 ± 1.52	2.636	0.011	51	0.724
	4.28 ± 1.65				

(datasets from SF to UNESS) in both groups, where all the participants were considered. The tests were two-tailed, were conducted at the 0.05 significance level and the assumption of equal variances was tested by F test (P < 0.02). This table includes the Student's *t*-test to compare the means of both groups for all the parameters considered. The data related to the number of collisions (COLL1 and COLL2) have been intentionally omitted, for the sake of clarity, since they were practically invariant to the selected treadmill. The results showed that while the time spent for the participants to complete short distances (TIME1) using the Virtuix Omni (57.07 ± 32.05) is significantly lower (t [52] = −2.63, p = 0.011, Cohen's d = −0.728) than using the Cyberith Virtualizer (77.53 ± 24.18), these statistical differences are not evident as the distances increase.

Concretely, there were are no statically significant differences between the results obtained with both VR platforms in TASK2 (t [51] = −0.81, p = 0.422, Cohen's d = −0.235). The cause for this may be the particular sliding mode the flat-based omnidirectional treadmill (Cyberith Virtualizer), which requires a period of user adaptation longer than that of the other VR treadmill. In any case, Fig. 7 shows the boxplot for the time spent by participant in TASK2 using both treadmills, where a slight improvement for the bowl-based omnidirectional treadmill (Virtuix Omni) is displayed.

Additionally, Table 1 shows statistically significant differences between the results obtained with both VR treadmills, in favor of the Virtuix Omni, from the results to the ergonomic factors (EF dataset),

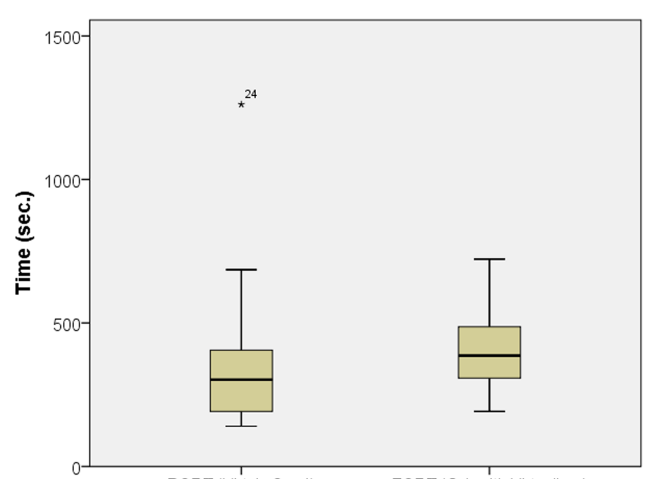

Fig. 7. Time spent for the participants to complete TASK2.

Table 2
Averages and standard deviations of the responses corresponding to the overall experiment for participants in Group A (first row for each parameter) and Group B (second row for each parameter).

Parameter	Questioner 1st	Questioner 2nd	t	p
TIME2	358.61 ± 238.30	266.49 ± 112.32	2.595	0.015
	398.56 ± 134.92	179.27 ± 76.41	7.332	0.000
EF	5.50 ± 0.90	4.70 ± 0.93	3.625	0.001
	4.67 ± 1.09	5.62 ± 1.13	−4.573	0.000
CF	3.65 ± 1.23	3.15 ± 1.29	4.982	0.000
	3.65 ± 1.21	5.16 ± 1.05	−5.850	0.000
DF	5.21 ± 1.35	4.07 ± 1.30	3.518	0.002
	4.72 ± 1.44	5.56 ± 1.22	−3.376	0.002
SCORE	5.36 ± 1.25	3.46 ± 1.53	5.087	0.000
	3.75 ± 1.54	5.54 ± 1.21	−5.529	0.000
UNESS	5.43 ± 1.52	4.25 ± 1.96	2.841	0.008
	4.21 ± 1.64	5.33 ± 1.55	−3.644	0.001

control factors (CF dataset) and other factors (OF dataset). These significant differences were also evident, in favor of the Virtuix Omni, when users rated the two alternatives (SCORE dataset, $t[51] = 3.90$, $p < 0.05$, Cohen's $d = 0.68$) or the usefulness provided by both of them to move comfortably in a virtual environment (UNESS dataset, $t[51] = 2.64$, $p < 0.05$, Cohen's $d = 0.72$).

Since most of the potential customers of this type of VR product would test both alternatives before making the final purchase, an evaluation was set up to detect the possible effects of using one of the two VR treadmills or the alternative [26]. In order to fulfill this goal, paired t-tests were calculated to the responses obtained from the participants that tested a VR treadmill and then, the other alternative. Table 2 shows the means and the standard deviations for the parameters which showed a statistically significant difference between the responses in both stages (collected in both questionnaires) of the experiment. The first row for each parameter shows the results for the participant in Group A, who tested the bowl-based omnidirectional treadmill (Virtuix Omni) first, and next the flat-based omnidirectional treadmill (Cyberith Virtualizer). Similarly, the second row for each parameter shows the results for the participants in Group B, who tested the VR devices in reverse order. Table 2 shows that the time spent to complete long virtual walks (TIME2) by both groups of participants decreases when they test a second VR treadmill. These results seem to indicate that the use of a second VR treadmill (regardless of the first option) adds a significant improvement in the learning and accommodation process to use this virtual device as a walking device in a virtual experience.

For the questions related to presence in virtual environments [23], there were no statistically significant differences for the sensory factors, realism factors and the 3D depth perception. As expected, participants produced similar responses related to these parameters, since both alternatives share a visual system based on Oculus Rift. However, the responses to the ergonomic factors, control factors and distraction factors shown in Table 2 are higher for Virtuix Omni regardless the order of evaluation. This behavior is also observed for the global (SCORE) and the usefulness scores (UNESS).

Fig. 8 shows the final user's preference, taking into account the order of test presentation, when they had to select one of the treadmills evaluated. Although the results for this preference were requested following three different criteria (as explained in Section 4.1), the responses were similar for all of them. In this sense, this figure shows that 75 percent of the users selected the Virtuix Omni as the VR treadmill that they liked the most (LIKE dataset). Moreover, this selection was performed by users regardless of which VR treadmill they started with.

Next, a correlation analysis determined the relationship between each of the independent parameters. Fig. 9 shows this analysis, expressed as a correlogram [27], for the responses given by the participants that tested the Virtuix Omni first. In this figure, the positives correlations are displayed in blue tones and the negative correlations in red tones. Moreover, the intensity of the colors and sizes of the circles are proportional to the correlation coefficients. At the bottom of the figure, the legend color shows the corresponding coefficients and the corresponding colors.

Fig. 9 shows a strong and significant correlation among all the parameters related to the sense of presence in Virtual Reality (from SF to OF). Moreover, there were other remarkable positive correlations between the realism (RF) with the global scores (0.574, $p < 0.001$), 3D depth perception (0.572, $p < 0.002$) and usefulness values (0.453, $p < 0.01$) indicated by the participants. This indicates that the final user's evaluation is related to the realism provided by the treadmills within the virtual walking environment. A similar correlation study was conducted with the datasets provided by the participants that tested the flat-based omnidirectional treadmill (Cyberith Virtualizer) first (Group B). In this case, there were similar correlations, but they were slightly weaker than in Group A.

Finally, a multifactorial ANOVA test was performed in order to take into consideration the following factors simultaneously: age, gender, and participant's profession. This test revealed two significant differences. Specifically, an analysis of variance on the LIKE dataset showed a significant primary effect of the participants' age ($F[4,16]$, $p = 0.044$, $\eta 2G = 0.439$). A Tukey post-hoc test confirmed that for participants aged 50 and older the selection of the treadmill that they like the most was significantly different to the rest of age ranges at $p < 0.05$. Another difference was that the final data included in the RECO dataset with respect to the combination of age and profession of the participant ($F[3,16]$, $p = 0.021$, $\eta 2G = 0.446$). A Tukey post-hoc test showed these recommendations (in terms of endorsing a given treadmill) provided by the group of mechanical engineering students aged 18–25 was significantly different at $p < 0.05$. Additionally, the post-hoc tests were repeated in our study correcting the p-values, according to the Bonferroni procedure, obtaining similar results.

6. Conclusions

The physical movement of the users has traditionally been a challenge in the Virtual Reality technologies for decades. Although omnidirectional locomotion platforms have been posed as a feasible solution to generate the feeling of walking, most of the approaches have lacked an affordable, intuitive, and ergonomic VR walking experience.

In this paper, we have presented a comparative study where we evaluated two new flat-based and bowl-based omnidirectional treadmills with 54 participants. These Virtual Reality treadmills are considered nowadays the cutting-edge solutions for the simulation of walking in virtual environments, lacking disadvantages of former alternatives.

From the results of this study, we can conclude that our primary hypothesis ("there would be significant difference between the performances of the VR treadmills evaluated") was not corroborated because there were no statistically significant differences between the bowl-based (Virtuix Omni) and the flat-based (Cyberith Virtualizer) omnidirectional treadmills when used for long-distance virtual walks. However, there were statistical differences in support of the bowl-based omnidirectional treadmill when the evaluation was performed in terms of presence. Second, the results confirmed our second hypothesis ("the participants would prefer the bowl-based treadmill") among different perspectives, such as overall preference, recommendation and usefulness, when potential gamers choose between bowl-based or flat-based treadmill to be part of their VR equipment. The reasons to prefer this treadmill were that bowl-based approach was easier to use (63%), reacted faster to the user's movements (21%) and was more comfortable (16%) than of the flat-based treadmill. Furthermore, the correlation analysis showed statically significant correlations among all the parameters related to presence, which in turn, are related to the global scores given by the participants of the experiment. In general terms, the result of this study could serve as a suggestion for the companies to

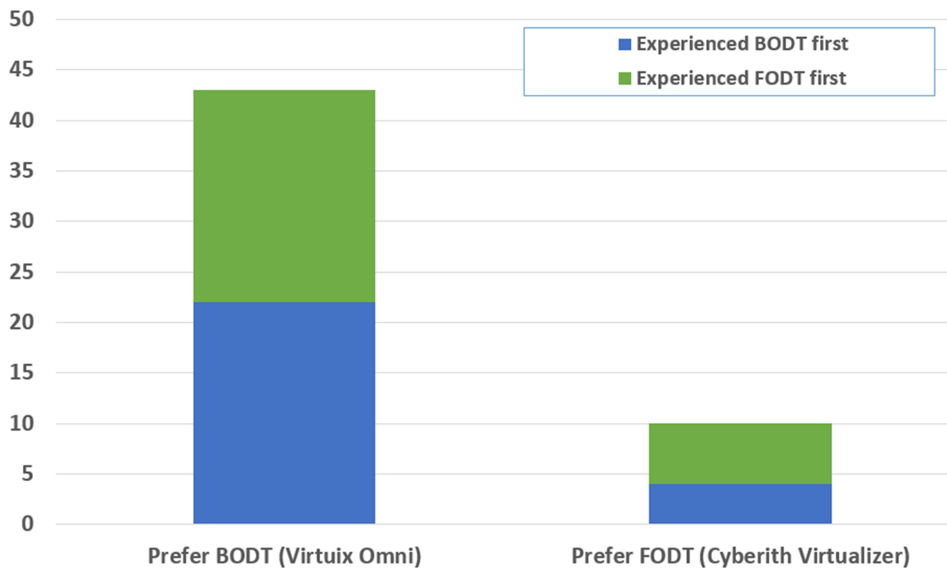

Fig. 8. Bar chart representation showing the final user's preference.

improve their products in future developments.

For future work, we plan to complete some hardware modifications at the elements included in floor of the Virtuix Omni in order to achieve a more natural user's movements detection. Moreover, we are already designing a comparative study with real users to evaluate the performance of the bowl based omnidirectional treadmills and the redirected walking techniques (RDW) [28], another solution to explore larger virtual environments within small tracking areas.

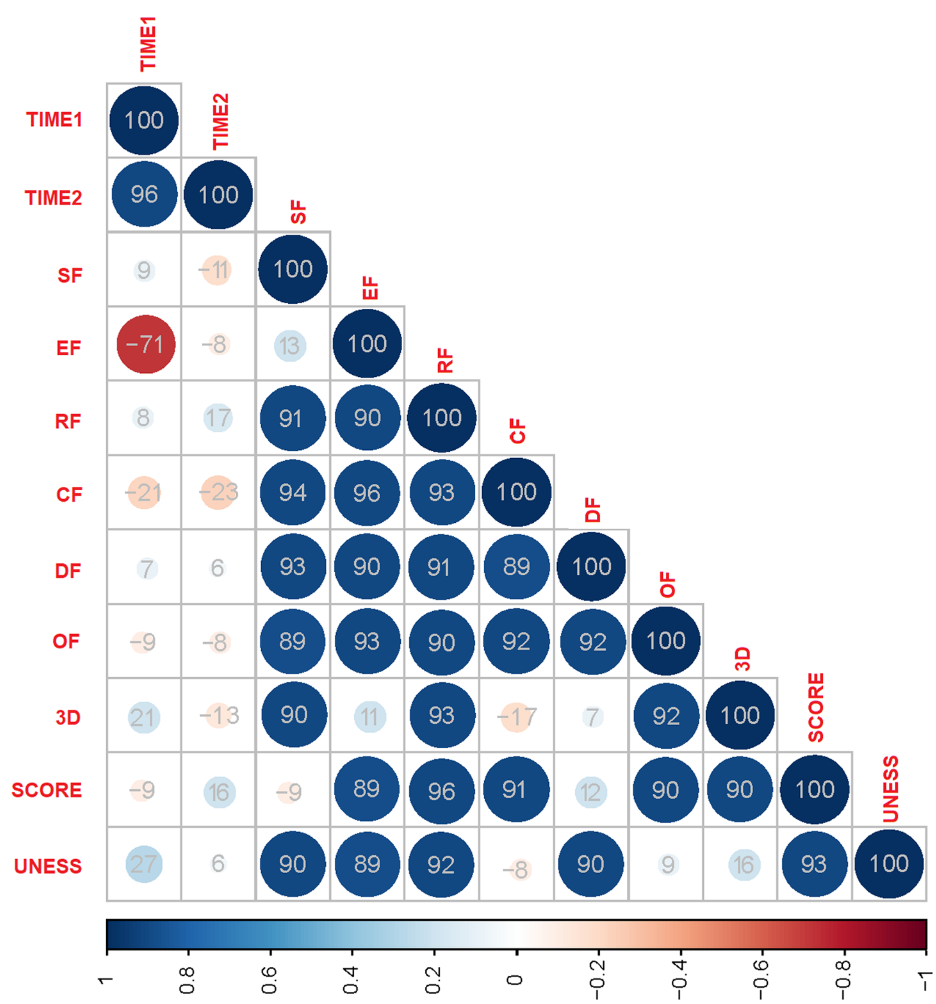

Fig. 9. Significant correlations detected in the first questionnaire for the users in Group A.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been supported by Spanish MINECO and EU ERDF programs under grants TIN2015-66972-C5-5-R, TIN2016-81840-REDT, and TIN2016-81850-REDC An example appendix.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.entcom.2020.100352.

References

[1] K.S. Hale, K.M. Stanney, Handbook of Virtual Environments: Design, Implementation, and Applications, CRC Press, 2014.
[2] R.P. Darken, D. Carmein, The omni-directional treadmill: a locomotion device for virtual worlds, in: Proceedings of ACM Symposium on User Interface Software and Technology (UIST), 1997, pp. 213–221.
[3] G. Hardiess, H.A. Mallot, T. Meilinger, Virtual reality and spatial cognition, in: International Encyclopedia of the Social and Behavioral Sciences, seconds ed. Editionial JD Wright, Elsevier, Oxford, UK, 2015, pp.133–137.
[4] H. Lee, S. Pyo, S. Park, J. Yoon, Design of the omni directional treadmill based on an Omni-pulley mechanism, in: Proceedings of 13th IEEE International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), 2016, pp. 889–894.
[5] A.D. Luca, R. Mattone, P. Robuffoano, H.H. Bulthoff, Control design and experimental evaluation of the 2D cyberwalk platform, in: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2009), 2009, pp. 5051–5058.
[6] T. Cakmak, H. Hager, “Cyberith Virtualizer- A Locomotion Device for Virtual Reality, Vienna University of Technology, 2014.
[7] KatWalk VR System, Retrieved from www.katvr.com, 2016.
[8] ROVR VR treadmill, Retrieved from www.wizdish.com, 2018.
[9] SpaceWalker Virtual Reality Walking Simulator, Retrieved from www.spacewalkervr.com, 2017.
[10] Virtuix Omni, Retrieved from www.virtuix.com, 2014.
[11] Cyberith Virtualizer, Retrieved from www.cyberith.com, 2016.
[12] Infinadeck Omnidirectional Treadmill, Retrieved from www.infinadeck.com, 2017.
[13] A. Pollatsek, A.D. Well, On the use of counterbalanced designs in cognitive research: a suggestion for a better and more powerful analysis, J. Exp. Psychol. Learn. Mem. Cogn. 21 (3) (1995) 785–794.
[14] K.V. Ruder, N.C. Nilsson, R. Nordahl, S. Serafin, An exploration of input conditions for virtual teleportation, in: Proceedings of the 24th IEEE Conference on Virtual Reality (IEEE VR 2017), 2017, pp. 341–342.
[15] Z. Wang, K. Bauernfeind, T. Sugar, Omni-directional treadmill system, in: 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, IEEE HAPTICS 2003. Proceedings, 2003, pp. 367–373.
[16] A. Stavar, L.M. Dascalu, L. M. and D. Talaba, Design, test and experimental validation of a VR treadmill walking compensation device, in: Doctoral Conference on Computing, Electrical and Industrial Systems. Springer, Berlin, Heidelberg, 2011, pp. 402–409.
[17] J. Linowes, Unity Virtual Reality Projects, Packt Publishing Ltd (2015).
[18] Oculus Rift CV1, 2016. Retrieved from www.oculus.com/rift.
[19] HTC Vive, 2016. Retrieved from www.vive.com.
[20] K. Hornbæk, Some whys and hows of experiments in human–computer interaction, Found. Trends® Hum.-Comput. Interact. 5 (4) (2013) 299–373.
[21] J.M. Morse, Determining sample size, Qual. Health Res. 10 (1) (2000) 3–5.
[22] D.C. Montgomer, G.C. Runger, Applied Statistics and Probability for Engineers, John Wiley and Sons, 2003.
[23] B.G. Witmer, M.J. Singer, Measuring presence in virtual environments: a presence questionnaire, Presence: Teleoperators Virtual Environ. 7 (3) (1998) 225–240.
[24] H. Regenbrecht, T. Schubert, Measuring presence in augmented reality environments: design and a first test of a questionnaire, Proceedings of the 5th Annual International Workshop Presence, (2002).
[25] Doug A. Bowman, Ryan P. McMahan, Virtual reality: how much immersion is enough? Computer 40 (7) (2007) 36–43, https://doi.org/10.1109/MC.2007.257.
[26] C.G. Greeno, Major alternatives to the classic experimental design, Fam. Process 41 (4) (2002) 733–736.
[27] T. Wei, M.T. Wei, Package ‘corrplot’, Statistician 56 (2016) 316–324.
[28] S. Razzaque, Z. Kohn, M.C. Whitton, Redirected walking, in: Proceedings of the ACM SIGGRAPH/EUROGRAPHICS conference, vol. 9, 2001, pp. 105–106.