Evaluation of a Low-Cost Virtual Reality Surround-Screen Projection System

Afonso Gonçalves, Adrián Borrego, Jorge Latorre, Roberto Llorens, and Sergi Bermúdez i Badia

Abstract—Two of the most popular mediums for virtual reality are head-mounted displays and surround-screen projection systems, such as CAVE Automatic Virtual Environments. In recent years, HMDs suffered a significant reduction in cost and have become widespread consumer products. In contrast, CAVEs are still expensive and remain accessible to a limited number of researchers. This study aims to evaluate both objective and subjective characteristics of a CAVE-like monoscopic low-cost virtual reality surround-screen projection system compared to advanced setups and HMDs. For objective results, we measured the head position estimation accuracy and precision of a low-cost active infrared (IR) based tracking system, used in the proposed low-cost CAVE, relatively to an infrared marker-based tracking system, used in a laboratory-grade CAVE system. For subjective characteristics, we investigated the sense of presence and cybersickness elicited in users during a visual search task outside personal space, beyond arms reach, where the importance of stereo vision is diminished. Thirty participants rated their sense of presence and cybersickness after performing the VR search task with our CAVE-like system and a modern HMD. The tracking showed an accuracy error of 1.66 cm and .4 mm of precision jitter. The system was reported to elicit presence but at a lower level than the HMD, while causing significant lower cybersickness. Our results were compared to a previous study performed with a laboratory-grade CAVE and support that a VR system implemented with low-cost devices could be a viable alternative to laboratory-grade CAVEs for visual search tasks outside the user's personal space.

Index Terms— H.5 Information Interfaces and Representation (HCI), H.5.1.b Artificial, augmented, and virtual realities, H.5.2.e Evaluation/methodology

1 Introduction

VIRTUAL Reality (VR) refers to computer-generated environments and digital simulations that provide a real-world-like experience, both from the interaction and exploration perspective [1], [2]. While there are different ways to produce VR, each system provides its specific level of immersion. According to Slater et al. [3], [4] immersion describes to what degree a system is extensive, surrounding, inclusive, vivid, matching, and self-representative. Consequently, immersion is associated with the number of sensory channels involved (extensive), the directionality of the stimulation and the natural modes such as stereopsis (surrounding), the number of sensory systems that are disengaged from reality (inclusive), the variety and richness of information (vivid), the match between our proprioceptive system and the information provided (matching), and the provision of a virtual body (self-representative). While these features are objective technological characteristics of a VR system and contribute to the realism of the experience [5], the personal traits can also modulate the way users experience a virtual environment (VE) or a VR system and promote differences among them. For this reason, it is also essential to measure the subjective perception experienced by users, the sense of presence being one of the most relevant factors. Presence has been described as the awareness of being immersed in a VE while ignoring the technology that mediates the experience, a sense of "being there" in the VE, instead of merely perceiving it [2].

To produce VR experiences of high immersive degree, different displays have been developed, including head-mounted displays (HMDs) [6] and stationary surround VR displays, such as cave automatic virtual environments (CAVEs) [7], [8]. HMDs are headsets that provide visual stimulation with eye disparity and, in the last years, also provide built-in head tracking. In the CAVE and similar systems, screens are fixed in the physical world and surround the user; external optical tracking systems usually provide head tracking. Information about the head pose is used to match the images displayed to the user's perspective. While recent technological developments and entertainment interest in HMDs have facilitated their commercial availability at reasonable costs, CAVE-like systems

- *A. Gonçalves is with the Madeira Interactive Technologies Institute (M-ITI), NOVA-LINCS, and Faculdade de Ciências Exatas e da Engenharia, Universidade da Madeira, Funchal, Portugal. E-mail: afonso.gonvalves@m-iti.org.*
- *A. Borrego is with the Neurorehabilitation and Brain Research Group, Instituto de Investigación e Innovación en Bioingeniería, Universitat Politècnica de València, Camino de Vera s/n, 46011 Valencia, Spain. E-mail: adborgon@upv.es.*
- *J. Latorre is with the Neurorehabilitation and Brain Research Group, Instituto de Investigación e Innovación en Bioingeniería, Universitat Politècnica de València, Camino de Vera s/n, 46011 Valencia, Spain, and NEURORHB. Servicio de Neurorrehabilitación de Hospitales Vithas, Río Tajo 1, 46022 Valencia, Spain. E-mail: jlatorre@i3b.upv.es.*
- *R. Llorens is with the Neurorehabilitation and Brain Research Group, Instituto de Investigación e Innovación en Bioingeniería, Universitat Politècnica de València, Camino de Vera s/n, 46011 Valencia, Spain, and NEURORHB. Servicio de Neurorrehabilitación de Hospitales Vithas, Río Tajo 1, 46022 Valencia, Spain. E-mail: rllorens@i3b.upv.es.*
- *S. Bermúdez i Badia is with the Madeira Interactive Technologies Institute (M-ITI), NOVA-LINCS, and Faculdade de Ciências Exatas e da Engenharia, Universidade da Madeira, Funchal, Portugal. E-mail: sergi.bermudez@m-iti.org.*

are still costly solutions, both in money and space, for data visualization in research laboratories and companies. In a recent paper [9], we presented the KAVE software for managing monoscopic surround-screen projection and motion parallax, which uses the low-cost RGB-D camera Kinect v2 (Microsoft, Redmond, USA) to provide head tracking, inspired by the work of J. Lee [10]. The KAVE aimed at providing a low-cost alternative and overcome some of the barriers that prevent CAVE-like systems' widespread use, such as proprietary software (and its costs), expensive tracking hardware, and strictness of the physical and hardware setup.

Although the KAVE software has shown to be a feasible alternative to create an immersive system exclusively using off-the-shelf, low-cost devices [9], the system's capability to elicit presence and cybersickness remains unexplored, as well as the quantification of the accuracy and precision of its tracking technology. To study some of the circumstances in which this system could be advantageous or comparable to the competition, we set out to explore our system in two controlled experiments, which allowed us a direct comparison with a previous study by Borrego et al. [11]. In the first, we measured the head tracking's accuracy and precision compared to a laboratory-grade optical tracking system in a controlled static scenario. In the second, we measured the sense of presence and cybersickness experienced by participants. With this, we aimed at answering the following two research questions: How accurate and precise is a low-cost tracking sensor (i.e. Kinect v2) in estimating the user's head position in a KAVE-powered CAVE? And, in a simple VR action space search task, to what extent can the KAVE induce presence while remaining cybersickness-free in a representative sample of healthy adults?

After occlusion, stereopsis (binocular disparity) and motion parallax are the two most relevant cues when estimating objects' depth in the observer's personal space (less than 2 m). While for distances less than 1 m, stereopsis outweighs motion parallax, at larger distances, motion perspective due to parallax is a better source for depth estimation [12]. However, both sources of information decline linearly with distance, and at 30 m are no longer reliable enough compared to other sources, thus defining the action space (2 m to 30 m) [12]. Most competing VR systems feature stereoscopic imaging, and therefore depth perception through stereopsis. Due to its monoscopic nature, this depth cue is not available in the KAVE. Because of this difference, we choose a task that does not depend on stereopsis to enable a valid comparison with systems featuring stereopsis. Thus, we focus our study on a visual search task happening mainly in the action space (slightly beyond arm's reach). Lastly, by replicating a previous experiment that compared a laboratory-grade CAVE and an HMD walking VR system, using the KAVE and a modern HMD instead, we could compare the KAVE to three alternative technologies. Comparing it with a modern HMD is relevant as their significant evolution in the past decade has changed the balance in the relation between presence and VR mediums, which previously favored CAVEs [13]. The comparison with a laboratory-grade CAVE allows examining our solution's advantages and disadvantages relative to this type of systems' state-of-art. Finally, the use of a large area walking VR draws the contrast with the other three technologies, tested in much more confined interaction areas, and allows for insight into how this can affect results.

2 Methods – Accuracy & Precision of the Head Tracking

To evaluate the accuracy and precision of the Kinect v2-based head tracking, we measured its position error and jitter in a 2.8 m by 2.8 m area, relative to a linear, four-camera ARTTRACK2 system (Advanced Realtime Tracking GmbH, Weilheim in Oberbayern, Germany), serving as the gold standard. Since the Kinect tracks human shapes and the ARTTRACK2 tracks IR markers, a medical upper-body mannequin with an IR marker placed in the space between the eyebrows (glabella) was used to provide a static tracking target for both systems. Measurements were registered by placing the mannequin in twelve intersection points of a 4x3 grid, with 60 cm x 80 cm spacing, at sitting (1.4 m), and standing height (1.7 m) (Fig. 1). The Kinect v2 was positioned 66 cm away from the ARTTRACK2 camera plane, aligned with the center of the grid at 80 cm from its closest point, at the height of 2.2 m, tilted down 30° (Fig. 2). The two closest corners of the grid were discarded as the Kinect v2 did not see them.

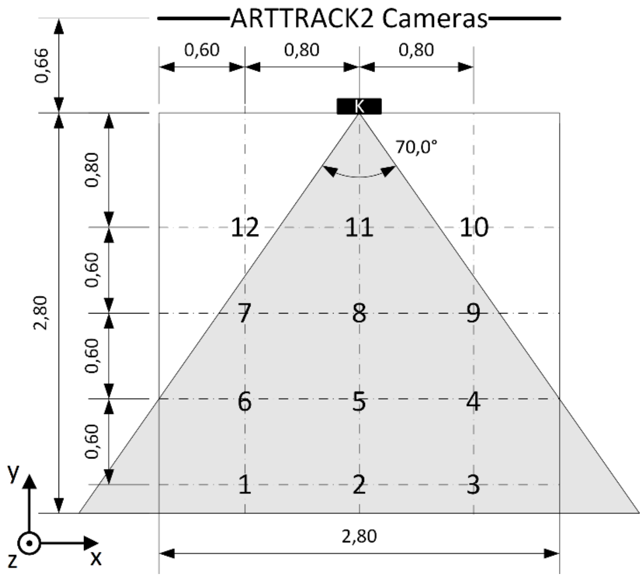

Fig. 1. Placement of the Kinect v2, its field of view (simplified), the grid positions (1 to 12) and their spacing in meters.

The mannequin was sequentially positioned at the different points; and for each of them, its position was registered with both tracking systems for 5 seconds at a sampling frequency of 30Hz.

Because the two tracking systems had different reference frames, the transformation matrix (translation and rotation) between them was estimated using Procrustes analysis [14]. This process finds the linear transformation that minimizes the sum of squared errors between two configurations of points where there is a correspondence between points. The transformation was applied to the Kinect v2 data, converting all measurements to the same reference frame and eliminating any systematic difference (offset) between the estimated positions of the marker attached to the mannequin and the head joint identified by the Kinect v2.

Accuracy of the measurements (e) was calculated as the mean difference, during the five seconds, between the mean position of the IR marker estimated by the laboratory-grade tracking system (X) and the position of the head joint estimated by the Kinect v2 at sample i ($\tilde{X}_i$),

$$e = 1/N \sum_{i=1}^{N} \left| X - \tilde{X}_i \right|, \quad (1)$$

where N is the total number of samples. Jitter (j) was calculated as the standard deviation of the Kinect v2 measurements,

$$j = \sqrt{\sum_{i=1}^{N} \tilde{X}_i^2 / N - \bar{X}^2}, \quad (2)$$

where $\bar{X}$ is the mean value of $\tilde{X}$.

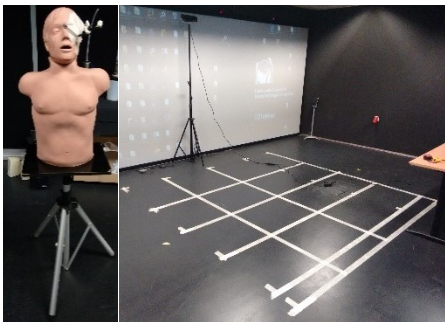

Fig. 2. The mannequin and tracking space used

3 Methods – Sense of Presence & Cybersickness

To determine the sense of presence and cybersickness that could be elicited by a surround-screen projection system using the KAVE software, we compared the reported experiences of a sample of healthy adults in two conditions. One after interacting with a low-cost implementation of a traditional CAVE system powered by the KAVE [9], the other after interacting with a modern HMD, HTC Vive. Additionally, we compared our results with the data from a previous study following the same procedure [11], in which participants interacted with two other VR setups, a laboratory-grade CAVE system and an HMD-based walking system.

3.1 Instrumentation

Two experimental setups were used in this study; they are described in sections 3.1.1 and 3.1.2. Additionally, we described the setups tested by Borrego et al. [11] in sections 3.1.3 and 3.1.4. A comparison of the four immersive solutions' characteristics is provided in Table 1.

3.1.1 Low-cost CAVE powered by the KAVE software

A practical deployment of the KAVE software was done on a low-cost CAVE [9] of standard configuration, three walls, and floor (shown in Fig. 3). Two walls on the sides and one at the front, describing 90-degree angles between them and with the floor. The walls are 2.8 m wide by 2.1 m tall, and the floor is 2.8 m wide by 2 m long, covering the area up to 2 meters from the front wall. Four Optoma GT1080 projectors (Optoma, New Taipei, Taiwan), with a 1080p image resolution and a throw ratio of 0.5:1, deliver monoscopic front-projection over the four surfaces. The system provides a horizontal FOV of 270° and a vertical FOV of 128° at its center point, and has a resolution of 1120 x 880 pixels per wall with a pixel density of 4 pixels per cm. A Kinect v2 is centered over the front wall and tilted at a downward angle of 30°. This sensor has a field of view of 70° and can track users up to 4.5 m, providing head tracking and human pose estimation, consisting of 25 joints, at 30 Hz, with an estimated latency of 66.66 ms [15]. The tracking area of this sensor is presented in gray shading in Fig. 1. The user's head position is used in real-time by the KAVE software, which applies it to the virtual cameras in the virtual environment, and continuously adjusts their projection matrices so that their frusta are perpendicular and framed with the respective projection surfaces. The VE images captured by the virtual cameras are projected in real time on the walls and floor, which generates motion parallax coherent with what the user would see if they were present and moving in the VE [9]. The summary of the immersive characteristics of this CAVE – KAVE is presented in Table 1. One single computer with a Quad-Core 3.4GHZ processor, 8GB of RAM, and Radeon RX 580 8GB graphics card runs the system. For improved readability, the "Low-cost CAVE powered by the KAVE software" is simply referred to as KAVE in the following sections.

Fig. 3. Low-cost CAVE powered by the KAVE software.

3.1.2 Commercial head-mounted display – HTC Vive

The HTC Vive was considered representative of modern HMD technology. It is an off-the-shelf HMD with a 1080 x 1200 per eye pixel resolution and a 110° FOV. It provides built-in head orientation and also head position tracking through a laser-based inside-out tracking system, called Lighthouse. This tracking technology has been estimated to have an accuracy ranging from 0.19 cm to 1.22 cm, a position jitter of 0.03 cm, orientation jitter of 0.02°, and latency ranging from 4.44 ms to 22 ms [6], [16], [17].

In this study, the same computer was used to operate both the HTC Vive and the KAVE.

3.1.3 Head-mounted display-based walking system

The system consists of an Oculus DK2 (Oculus VR, Menlo Park, USA), a PlayStation Eye Camera (Sony Corporation, Tokyo, Japan) attached to it pointing upwards, and a 3.78 m by 5.7 6m pattern of 442 fiducial markers installed on the ceiling [11], depicted in Fig. 4. The system runs on a laptop with an 8-core Intel Core i7 Haswell 2.50 GHz, 8 GB of RAM, and an NVIDIA GeForce GTX 860M 2GB. It uses the Oculus DK2 HMD native orientation tracking while the position tracking is done inside-out through the camera input, *i.e.*, the HMD tracks its position relative to the markers. When the user is at standing height, this system has a mean positional accuracy of 0.94 cm, a mean jitter of 0.10 cm, and a mean latency of 120 ms. The display specs are the standard for an Oculus DK2, a FOV of 100°, 960 x 1080 pixels per eye resolution, and stereoscopy.

Fig. 4. Walking VR System, image adapted from [11].

3.1.4 Laboratory-grade CAVE

A CAVE, shown in Fig. 5, with four projection surfaces (three 3.5 m wide by 2 m high walls and floor), was used (Barco N.V., Kortrijk, Belgium). Stereo images with an 1868 x 1200 resolution are provided by four projectors F35 AS3D WUXGA (ProjectionDesign, Fredrikstad, Norway). Images are back-projected on the vertical walls and mirror-projected on the floor. Stereoscopic immersion is provided through 3D glasses, the Crystaleyes 3 (StereoGraphics, San Rafael, USA), which have a constellation of infrared reflective markers attached to its frame. The glasses' position and orientation are estimated through four infrared ART-TRACK2 tracking cameras (Advanced Realtime Tracking GmbH, Weilheim in Oberbayern, Germany). The system runs on five high-end graphics computers equipped with Intel Xeon CPU ES-2620 @ 2.00 GHz, 16 GB of RAM, and NVIDIA Quadro 5000 graphics cards.

Fig. 5. Laboratory-grade CAVE, image adapted from [11].

3.2 Procedure

The virtual environment from Borrego et al. [11] was used with some modifications. It consists of a supermarket aisle with two 4 m long by 2 m high shelves (6 racks) filled with 72 different soda types and corresponding price tags. The distance between shelves was adjusted from 1.5 m to 2.5 m relative to the original environment so that users could ambulate laterally. This VE provides a surrounding, generic scenario with lots of information in the participant action space, which was used for a visual search task. Two instances of the same Unity 3D VE were built for this study, one with the KAVE plugin that uses the projectors for imaging and the Kinect for tracking, another with Steam VR

Table 1

Immersive Characteristics of the Four VR Systems Under Study.

Immersive characteristics	Low-cost CAVE with KAVE	Head-mounted display – HTC Vive	Head-mounted display-based walking system	Laboratory-grade CAVE
Extensive	Visual, Auditive	Visual, Auditive	Visual, Auditive	Visual, Auditive
Surrounding	Monoscopic, 270° H x 128° V @ center	Stereoscopic, 360° H x 180° V, FOV 110°	Stereoscopic, 360° H x 180° V, FOV 100°	Stereoscopic, 270° H x 120° V @ center
Inclusive	Partially visual	Visual, Auditive, Wearable	Visual, Wearable	Partially visual, 3D Glasses
Vivid	4 x 1120 x 880, ≈4 p/cm	1080 x 1200	960 x 1080	4 x 1868 x 1200, ≈5.5 p/cm
Matching	Body tracking	Head tracking	Head tracking	Head tracking
Self-representation	Full body	None	None	Full body
Cost	≈5.000€	≈600€ + PC		≈200.000€

that uses the HTC Vive for imaging, together with two Lighthouse base stations for tracking. The physical space for both conditions was inside the 2.8 m x 2.8 m walled KAVE. Therefore, a 1.5 m x 1 m semi-transparent blue area with two footprints was added to represent the area where the user could freely move, as shown in Fig. 3 and Fig. 6. This served two purposes, ensure the KAVE users would not move forward (outside of the Kinect frustum) and avoid HMDs wearers from bumping into the real walls. Like in the study of Borrego et al. [11], a one-handed controller thumb analog joystick was used to virtually move the participant along (translation only) the longitudinal axis of the 4 m long supermarket aisle. As the aisle was longer than the experimental space (2.8m), the above mentioned blue area virtually moved together with the participant, remaining static relative to the participant point of view.

The study was designed as a two-condition repeated measures experiment where every participant experimented once in each condition, KAVE and HTC Vive. Participants were counterbalanced to avoid the order effect; thus, half of them were randomly chosen to experience one condition first and the other on a later date, the other half experienced the conditions in the opposite order.

At the beginning of the first session, participants were informed about the procedure, provided informed consent to participate in the study, and answered a brief questionnaire about their age, gender, education level, and video game experience, the latter in a 10-point Likert scale. Immediately before the experiment, they were guided to the center of the KAVE space. In the HTC Vive condition, they were assisted in setting up the interpupillary distance and putting the HMD. Then, participants had 5 minutes of free interaction with a basic version of the virtual environment, where the sodas and price tags were removed from the shelves. After this training time, the experiment started, and participants were asked to find the price of different items in the complete VE, which had the shelves filled with drinks and the price tags. Specifically, participants were given an item name, short description and were asked about its price. Once the correct price was answered, a new item was named, up to either a maximum of 5 items or 5 minutes had elapsed. Participants could move naturally inside the designated tracking area and use the joystick to move further along the aisle.

After the first assigned experimental condition, participants were asked to rate their cybersickness on a 7-point Likert scale. Then they reported their sense of presence in the original Slater-Usoh-Steed Questionnaire [18] (SUS) and a modified version of the Presence Questionnaire [19] (MPQ), which were previously applied in combination with the VE used in this study [11]. The SUS and MPQ are 3-item and 21-item questionnaires, respectively, rated on a 7-point Likert scale. They were then asked to return on a later date to repeat the same procedure with the other experimental condition.

Fig. 6. The virtual environment used in the study.

3.3 Participants

Healthy participants over 18 years old with no motor or cognitive impairment were recruited for this study from the faculty and student body of the University of Madeira. Thirty-two participants were recruited, of which 30 completed the study (Table 2, Current Study column). All provided informed consent before participation in the study. To guarantee this sample's equivalence with the participants in a previous study (Table 2, Previous Study column), we compared them across their characteristics. There were no significant differences between samples except for the years of schooling, with the participants from this study having slightly less (Median = 19) than the previous (Median = 21), U = 444.0, z = -2.55, $p < .05$.

Table 2
Characteristics of the Participants from Each Study

	Current Study	Previous Study [11]
Gender ratio	14 ♂ / 16 ♀	26 ♂ / 21 ♀
Age (years)	28.25 ± 5.6	28.1 ± 5.3
Years of Schooling (years)	19.83 ± 3.7	22.1 ± 4.4
Videogames Exp. [1-10]	6.83 ± 2.8	5.8 ± 3.3

3.4 Analysis

Questions of the Presence Questionnaire were divided into four components: visual aspects, interaction, consistency with the real world, and subjective factors [11]. Wilcoxon's T-tests were used to compare the repeated measures results from the KAVE and HTC Vive conditions, whereas Kruskal-Wallis was used to find differences between the independent measures of the KAVE, CAVE and Walking VR. The Mann-Whitney's U test, with Bonferroni's correction, was then used for the posthoc analysis between the KAVE and the other two systems. The significant difference level was set at 0.05, two-tailed. SPSS Statistics, version 22 (IBM®, Armonk, NY, USA) was used to analyze the data.

4 Results

4.1 Accuracy & Precision of the Head Tracking

The mean, standard deviation, and norm of these values are shown in Table 3.

Table 3
Mean ± Standard Deviation Values of Accuracy and Jitter Across the Ten Valid Grid Positions at the Two Tested Heights for the Kinect v2.

Accuracy error (cm)	Head @ 140 cm	Head @ 170 cm
X axis	0.73 ± 0.57	0.63 ± 0.46
Y axis	1.07 ± 0.75	1.16 ± 0.78
Z axis	1.04 ± 0.71	0.29 ± 0.18
Norm	1.66 ± 1.18	1.35 ± 0.92
Jitter (cm)	**Head @ 140 cm**	**Head @ 170 cm**
X axis	0.02 ± 0.01	0.02 ± 0.01
Y axis	0.03 ± 0.01	0.02 ± 0.01
Z axis	0.02 ± 0.02	0.01 ± 0.00
Norm	0.04 ± 0.02	0.03 ± 0.01

4.2 Sense of Presence & Cybersickness

In this section, we first present the experiment results measuring both cybersickness and the elicited sense of presence in two new conditions, the KAVE and HTC Vive HMD. Then we present the comparison of our results with the ones obtained by Borrego et al. [11], where the conditions CAVE and Walking VR correspond to a laboratory-grade CAVE and the authors' modified HMD.

4.2.1 Comparison between KAVE and HTC Vive

When reporting sickness levels, users felt significantly less sick in the KAVE (Median = 1) than in the HTC Vive (Median = 2), $T = 22.5$, $z = -2.614$, $p < 0.05$, $r = -.48$. Presence SUS levels were 2 points lower in the KAVE (Median = 14) than in the HTC Vive (Median = 16). This difference was found to be significant, $T = 62$, $z = -3.221$, $p < 0.05$, $r = -.59$. Presence Questionnaire levels in the KAVE (Median = 100) did not differ significantly from those in the HTC Vive (Median = 103), $T = 202.5$, $z = -.325$, $p = .745$. The same was true for all its components. For comparison with the previous study results, the means, standard deviations, and graphical representations of the response distributions can be seen in Table 4 and Fig. 7.

Table 4
Mean and SD of the Dependent Variables Measured in the KAVE and Vive Study Conditions.

VARIABLE		KAVE	HTC VIVE	p
SICKNESS	[1 - 7]	1.73 ± 1.17	2.47 ± 1.63	p < 0.05
PRESENCE SUS	[3 - 21]	13.23 ± 2.75	15.73 ± 2.90	p < 0.05
M. PRESENCE Q.	[21 - 147]	99.30 ± 0.05	100.73 ± 9.23	.745
VISUAL	[1 - 7]	4.47 ± 0.53	4.47 ± 0.54	.386
INTERACTION	[1 - 7]	4.19 ± 0.52	4.21 ± 0.68	.691
CONSISTENCY	[1 - 7]	5.17 ± 0.97	5.44 ± 0.79	.147
SUBJECTIVE	[1 - 7]	5.47 ± 0.84	5.57 ± 0.63	.897

4.2.2 Comparison between KAVE and CAVE & Walking VR

The data from the 47 participants of Borrego et al. [11] experiment, regarding presence from the SUS and Modified Presence Questionnaires, were reanalyzed for comparison with our experimental data. Their means and the standard deviation are presented in Table 5.

Presence was significantly affected by the VR system used, as measured both by the SUS $H(2) = 29.084$, $p < 0.05$, and the MPQ $H(2) = 24.767$ $p < 0.05$. Follow up tests

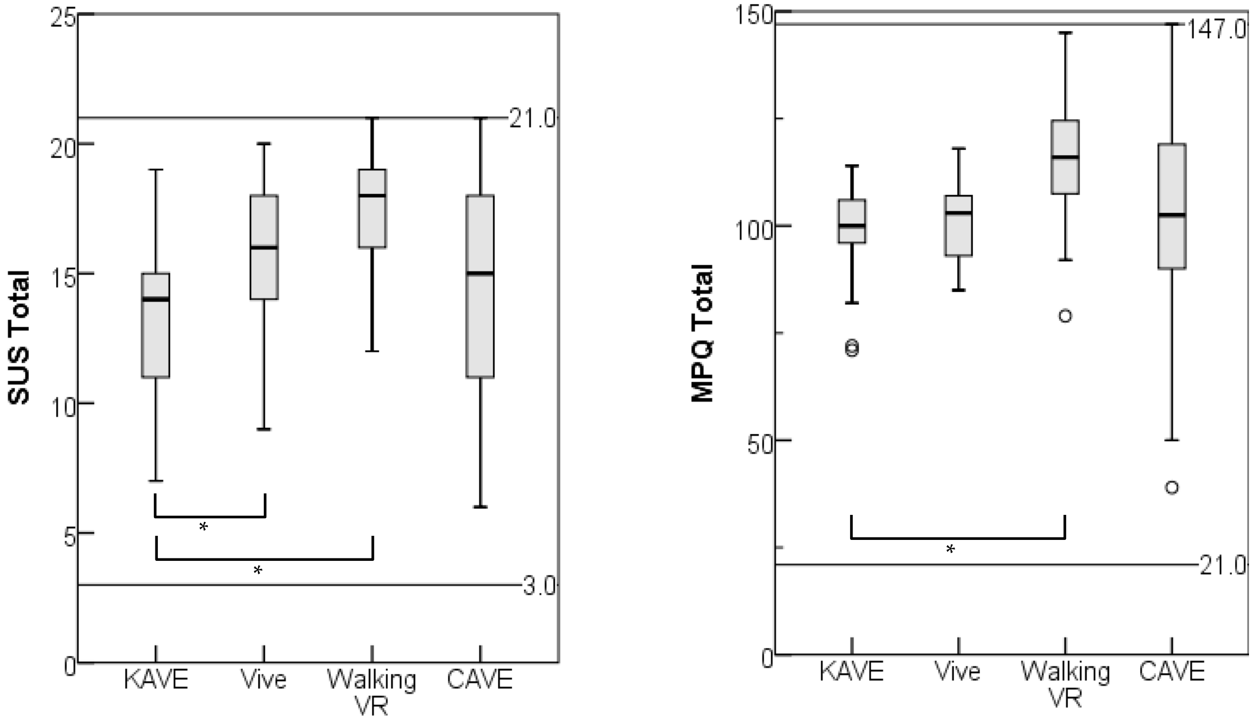

Fig. 7. The Slater-Usoh-Steed and Modified Presence Questionnaire scores for each of the VR systems used. The asterisk indicates significant differences between the KAVE and the other systems.

showed that presence SUS levels were significantly lower in the KAVE (Median = 14) than in the Walking VR (Median = 18), U = 174.5, z = -5.57, $p < 0.025$, r = -.63. This was also the case for Presence Questionnaire, where they were significantly lower in the KAVE (Median = 100) than in the Walking VR (Median = 116), U = 200.5, z = -5.27, $p < 0.025$, r = -.60. Presence SUS levels in the KAVE (Median = 14) did not differ significantly from those in the CAVE (Median = 15), U = 551, z = -1.62, p = .106. Neither did the Presence Questionnaire levels, the KAVE (Median = 100) did not differ significantly from the CAVE (Median = 102.5), U = 601, z = -.95, p = .344. These differences are shown in Fig. 7.

Table 5
Mean and SD of the Subjective Parameter Measured in Borrego's et al. [11] Study.

VARIABLE		WALKING VR	CAVE
PRESENCE SUS	[3 - 21]	17.57 ± 2.42	14.61 ± 4.42
M. PRESENCE Q.	[21 - 147]	116.68 ± 14.24	104.46 ± 22.74

5 Discussion

5.1 Accuracy & Precision of the Head Tracking

The accuracy of the Kinect v2 varied from 1.35 cm to 1.66 cm, slightly worse than the worst reported case for the HTC Vive, 0.19 cm to 1.22 cm; the same applies to its standard deviation that gives a notion about the difference of accuracy between positions on the grid (±1.18 cm). Increased accuracy at standing height can be observed, particularly in head height estimation, which had an average accuracy of approximately 3 mm. Anterior-posterior accuracy presented the worst results, and the mean accuracy on the horizontal plane (XY) was at centimeter-level, 0.63 cm to 1.16 cm. The measurements revealed a half-millimeter level jitter, which indicates a precise estimation of the head position in our KAVE, similar to the other systems [6], [11]. The Kinect head position accuracy results of one to two centimeters are consistent with what was reported by Otte et al. [20], who evaluated the Kinect v2 sensor tracking accuracy during landmark movements for possible clinical use. Considering that natural human head motion can average 2 cm when standing and looking at static images [21], a 2 cm offset and 1 mm jitter in head position estimation is considered sufficient for the intended purpose.

5.2 Feeling of Cybersickness

Participants reported significantly lower levels of sickness in the KAVE than in the HTC Vive. This difference can be a consequence of two main characteristics of these systems. First, nausea can result from the latency between head movement and scene update (motion to photon) [22]. Although this was not measured in the study, in surround-screen displays such as the KAVE, scenes essencially do not change due to head rotations, and they are already projecting close approximations of the next frame around the user [22]. This increased immediacy of the system at the cost of rendering images that might be outside of the user's FOV is responsible for lowering the apparent latency to head rotation and therefore minimizing one of the leading causes of cybersickness. Second, motion sickness is caused by inconsistencies between visual and vestibular stimulation regarding the existence of movement [22]. According to the rest frame hypothesis [23], it is provoked when what is perceived as a rest frame provides cues that conflict with this resting state and do not match the users' physical inertial environment. Because the KAVE is only partially vision-inclusive in its immersive characteristics (usual for CAVE-like systems), it lets users see part of the real world in their peripheral vision, such as the top structure, ceiling, and back wall curtain. Hence, allowing participants to use the real world as a rest frame lowers the amount of visual information that contradicts their vestibular system. This result, together with the fact that presence was found lower for the KAVE, is consistent with work suggesting that presence is related to the degree to which a selected rest frame is determined by the virtual interface [23]. In the KAVE, the real-world rest-frame visual cues could have affected both, lowering the feeling of presence and suppressing sickness.

5.3 Sense of Presence

During our experiment, participants stated a lower sense of presence with the Slater-Usoh-Steed questionnaire [18] (SUS) in the KAVE system than with the HTC Vive HMD, with a large effect size being detected. However, the Modified Presence Questionnaire [11], [19] differences were non-significant. This could be due to its questions being more numerous and broader in scope, leading to finer granularity results in a 21 to 147 score range than the SUS 3 to 21 score range. These results are consistent with Borrego et al. [11], which point to a lower sense of presence experienced by the participants in a laboratory-grade CAVE than in a room-scale tracked HMD. In their case, this was identified on both questionnaires. In summary, the Walking VR was better than both CAVE systems, and the HTC Vive better than the KAVE in one of the two questionnaires.

Despite the high levels of presence promoted by all four systems, the question of why there are differences is important. Since the experimental task and virtual environment were the same across conditions, differences in the feel of presence must have originated in the immersive characteristics of each system and how they relate with the particular visual search task used. Table 6 summarizes the main differences between systems in terms of immersive characteristics, where the dark shade represents the better and the lighter the worse. Considering significant differences found in this study, we can argue that differences were the cumulative effect of stereoscopy, full surround, no shadows and visual inclusiveness that the HTC Vive added that made it superior to the KAVE. Contrasting our experimental data with the one from Borrego et al. [11] allowed the comparison between a KAVE powered CAVE system and a professional laboratory-grade CAVE. The results revealed that the KAVE was no different from a laboratory-grade CAVE regarding the participants' feeling of

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2021.3091485, IEEE Transactions on Visualization and Computer Graphics

presence elicited. Hence, it seems to indicate that just the stereoscopy and lack of shadows (due to back-projection) that the CAVE provided was not enough to differentiate it from the lower cost KAVE. While this seems to point that stereopsis was not a significant immersive characteristic driving presence in this task, we must keep in mind that the task took place outside of the personal space, and that beyond the arms reach the relative importance of binocular disparity is diminished. This result is very encouraging as both systems are entirely different regarding technical specifications and cost. They both extend to the visual and auditive senses (audio was not included in the experiment) and provide similar limited surrounding immersion. Their field of view (FOV) over the VE depends on the user's head position. Concerning inclusiveness, neither of them completely shuts down any senses. The KAVE has the rare advantage of not requiring the user to wear any device or tracker. Matching in the KAVE system is defined by the capability of the Kinect v2 sensor to track 25 joints of the user's body, complemented by the user self-representation inside the VE. This means that if the VE affords it, the user's body can interact with virtual elements. In this experiment, no interaction other than ambulation was considered. Hence, if other types of interaction were required, it could positively influence the feeling of presence in the KAVE. The KAVE – CAVE costs around 5.000€ to build with commercial-grade hardware (3.200€ for the four projectors, 1.200€ the computer, 600€ Kinect v2 and physical wall structure) and runs on our KAVE free and open-source software, thus avoiding software license costs. Although the estimated cost of the CAVE used in our study [24] (200.000€) is far from the estimated cost of the original CAVE and CAVE2 systems (2.000.000$ and 926.000$ [8], [25]), it is still considerably above alternative low-cost CAVEs, such as the CryVE (19.300€ [26]). Here we have pushed this limit by presenting an even cheaper solution for CAVEs, and despite its lower specifications, it produced comparable subjective responses from the experiment participants.

Given the results, our second research question was answered, and the hypothesis was partially confirmed. In a simple VR action space visual search task, the KAVE can elicit similar presence levels to traditional CAVEs while keeping cybersickness low. However, results are not conclusive when comparing it to HMDs.

It is essential to ground the results and discussion to the task used in this study, as a different task could have led to different results. The two most important elements that defined the task were: First, the space in which it took place, virtual elements were always 1 m to 4 m away from the user. We speculate that longer distances would not produce different results between the systems. Keeping the virtual elements far enough from the user limits interaction and how they are perceived, as the binocular disparity is decreased. Second, the VE's short and linear nature, a 4 m long narrow aisle, only required exploration of the participant's field of regard. Hence, no mental representations of the environment had to be built, like when navigating a maze.

These results build the knowledge about our KAVE implementation and help us understand under what conditions the use of this system might be desirable. Our KAVE is an implementation of a low-cost CAVE and therefore maintains the specific advantages of CAVE systems over HMDs. Some of these advantages are no encumbrance of wearing a display mounted on the head, the use of peripheral vision due to large FOV, and the possible addition of real elements mixed with the virtual, such as a vehicle cockpit or control console of a machine [27]. Also, in the case of experiments required to be shared by multiple people seeing the same virtual elements or when wearing an HMD is not practical. The use of such a system is justifiable in the same way a CAVE is, except for experiences that require virtual elements to be present in the user's personal space. Meanwhile, in the context of VR, the addition of whole-body tracking offers an increased interaction potential, which was not studied in this work. However, we expect these features to be adopted to develop VR exergames (highly immersive exercise video games) where Kinect-like sensors can be used for its intended purpose of a game controller and natural user interface (NUI), such as in [28], [29].

6 Conclusions

In this work, the results from 2 experiments involving the KAVE are presented and discussed. We intended to evaluate a Kinect v2 sensor's accuracy in head-tracking and validate a KAVE implementation of a CAVE in eliciting the feeling of presence in a VE exploration task constrained to the action space. This CAVE implementation was done using the KAVE projection management software introduced

Table 6
Different Immersive Characteristics of the Systems Tested.

Main Differences	Low-cost CAVE with KAVE	Head mounted display – HTC Vive	Head mounted display-based walking system	Laboratory-grade CAVE
Stereoscopic	No	Yes	Yes	Yes
Field of view	Variable	110	100	Variable
Surround	Partial	Full	Full	Partial
Shadows	Yes	No	No	Floor
Inclusiveness	Partial	Yes	Yes	Partial
Wearable	No	HMD	HMD	Glasses
Area	2.8 m x 2.8 m	2.8 m x 2.8 m	3.78 m x 5.76 m	3.5 m x 3.5 m
Control	Controller	Controller	Ambulation	Controller

before [9] and low-cost, commercial-grade hardware. This system uses a Kinect v2 sensor for body tracking, and therefore is non-intrusive, and no equipment needs to be worn by users. In the first experiment, we found that the Kinect v2 is accurate enough to provide real-time head position estimation to the KAVE software, with a 1.66 cm average error, and it can be used to track the user's head while driving a VR experience. In the second study, the KAVE was tested for its cybersickness and presence-inducing capability directly against an HTC Vive in a repeated measures experiment and indirectly against a laboratory-grade CAVE and a room-scale Oculus DK2 in an independent samples study. The experimental task consisted of a local visual search of the VE at 1 m to 4 m distances, where the importance of binocular vision is reduced and featured no interaction. Results show that, while both CAVEs produced lower feelings of presence than HMDs, the KAVE was no different from a laboratory-grade CAVE. Together with the lower cybersickness produced, this result shows that our immersive surround-screen VR system solution (KAVE) is a feasible alternative to the traditional CAVEs in research when dealing with similar conditions. Without losing the feel of presence, relatively to other CAVEs, it adds three main advantages: it provides an opportunity to the budget-constrained scientific community due to the low implementation cost, the user does not have to wear any apparatus, and it supports full-body tracking. Beyond those advantages, its versatility to other configurations besides CAVEs, such as interactive VR walls, floors, and screens, makes it a tool that facilitates access, prototyping, trial, and improvisation of what are traditionally permanent and complex installations.

7 Limitations and Future Work

The KAVE software evaluation was limited by being tested in only one setup, a low-cost CAVE made of consumer electronics grade and gaming devices. The same software could have achieved better results if used in the laboratory-grade CAVE (retro-projection with higher resolution projectors) or used the ARTTRACK2 system instead of the Kinect v2 camera. A similar limitation is valid for the HTC Vive HMD, which was not used up to its full potential. The HTC Vive affords much larger tracking spaces than what was used and can be made wireless since the Vive Wireless Adapter is available. Given this wireless capability and a tracking space large enough to accommodate the whole VE, to not depend on a joystick for navigation along the aisle, we speculate that a higher level of presence, comparable to or higher than those of the HMD-based walking VR system, could be achieved.

The task used in this study, a visual search task in action space, constrains our conclusions to similar tasks and settings. Keeping the visualization distances beyond arm's length, not supporting interaction, or requiring complex navigation, prevents conclusions on how these systems compare to each other in other tasks, especially those with different interaction modalities.

The accuracy and precision of the Kinect v2 in tracking the user's head were measured in a static scenario; results might have differed if the target was moving. Still, regarding Kinect performance, it remains unknown if its head position and orientation estimation would be accurate and precise enough to support binocular visualization in a surround projection system.

Concerning the study design, using two samples of users for four systems, one sample for each pair of systems, is a limiting factor. In ideal conditions, either one sample per system should have been used, or one sample should have tested all systems. However, that was not possible, and the data analysis was performed to minimize interference. The differences between KAVE and HTC Vive were analyzed first in a classical within-subjects study. However, in comparing the KAVE with existing data from the CAVE and Walking VR HMD, the latter two shared the same participants, which could have had an effect. The randomization of conditions mitigated the order effect that could have been present in comparing the KAVE to the CAVE, given that half the participants only experimented with HMDs after.

The results of this research lead to some interesting questions that should be followed by future work. Given that the KAVE was the only system without stereography and its results did not differ from the laboratory-grade CAVE, it is relevant to question how would the KAVE fare in a test featuring immersion in the personal space. Also, it is relevant to quantify the importance of stereopsis as an immersive characteristic in the feeling of presence elicited. Our experiment consisted of a VR exploration task, meaning that the interaction domain was not explored. This, unfortunately, left unanswered the question of the role of VE interaction in the sense of presence experienced by users.

While the KAVE software already supports head-tracking through any system sending UDP messages in the ARTTRACK2 format, the discontinuation of the Kinect v2 is an obstacle to its adoption. For it to compete or be relevant, its future development should address this limitation to tracking. Adding support for new off-the-shelf solutions such as Azure Kinect (Microsoft, Redmond, USA) or Intel RealSense cameras (Intel, Santa Clara, California) would provide an immediate solution with a possible but uncertain increased performance [30]–[32]. Alternately, creating an abstract layer between the software and the sensor could make it sensor agnostic. Nevertheless, the open-source nature of the KAVE makes it easily accessible and modifiable by the community.

Future, current, and concrete uses of the KAVE are being planned, developed, and done by this work's authors. It takes the form of VR exergames and functional fitness assessment VEs aimed at the elderly population. This is achieved through a combination of virtual tours and ecologically valid VR experiences that can increase the transfer of skills to the real world by creating a high sense of presence.

Contributions and Acknowledgment

All authors contributed to the paper. Afonso Gonçalves and Sergi Bermúdez i Badia run the experiments on the feeling of presence with the KAVE and HTC Vive, which replicated the study from Adrian Borrego, Jorge Latorre, and Roberto Llorens, who provided the data collected with the CAVE and walking VR system from their paper [11]. Afonso Gonçalves collected the data from the accuracy measures with Adrian Borrego, Jorge Latorre, and Roberto Llorens.

This work was supported by the Fundação para a Ciência e Tecnologia through the AHA project (CMUPERI/HCI/0046/2013), by the INTERREG program through the MACBIOIDI project (MAC/1.1.b/098), LARSyS (UIDB/50009/2020), NOVA-LINCS (UID/CEC/04516/2019), by Fundació la Marató de la TV3 (201701-10), and the European Union through the Operational Program of the European Regional Development Fund (ERDF) of the Valencian Community 2014-2020 (IDIFEDER/2018/029).

References

[1] G. C. Burdea and P. Coiffet, *Virtual Reality Technology*, 2nd ed. John Wiley & Sons, 2003.

[2] J. Jerald, *The VR Book: Human-Centered Design for Virtual Reality*. Morgan & Claypool, 2015.

[3] M. Slater, V. Linakis, M. Usoh, R. Kooper, and G. Street, "Immersion, Presence, and Performance in Virtual Environments: An Experiment with Tri-Dimensional Chess," 1996, pp. 163–172. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.34.6594

[4] M. Slater and S. Wilbur, "A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 6, pp. 603–616, Dec. 1997, doi: 10.1162/pres.1997.6.6.603.

[5] D. A. Bowman and R. P. McMahan, "Virtual Reality: How Much Immersion Is Enough?," *Computer*, vol. 40, no. 7, pp. 36–43, Jul. 2007, doi: 10.1109/MC.2007.257.

[6] A. Borrego, J. Latorre, M. Alcañiz, and R. Llorens, "Comparison of Oculus Rift and HTC Vive: Feasibility for Virtual Reality-Based Exploration, Navigation, Exergaming, and Rehabilitation," *Games for Health Journal*, vol. 7, no. 3, Jun. 2018, doi: 10.1089/g4h.2017.0114.

[7] C. Cruz-Neira, D. J. Sandin, T. A. DeFanti, R. V. Kenyon, and J. C. Hart, "The CAVE: Audio Visual Experience Automatic Virtual Environment," *Commun. ACM*, vol. 35, no. 6, pp. 64–72, Jun. 1992, doi: 10.1145/129888.129892.

[8] C. Cruz-Neira, D. J. Sandin, and T. A. DeFanti, "Surround-screen Projection-based Virtual Reality: The Design and Implementation of the CAVE," in *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*, New York, NY, USA, 1993, pp. 135–142. doi: 10.1145/166117.166134.

[9] A. Gonçalves and S. Bermúdez, "KAVE: Building Kinect Based CAVE Automatic Virtual Environments, Methods for Surround-Screen Projection Management, Motion Parallax and Full-Body Interaction Support," *Proc. ACM Hum.-Comput. Interact.*, vol. 2, no. EICS, p. 10:1-10:15, Jun. 2018, doi: 10.1145/3229092.

[10] Johny Chung Lee, *Head Tracking for Desktop VR Displays using the WiiRemote*, (Dec. 21, 2007). Accessed: Mar. 06, 2020. [Online Video]. Available: https://youtu.be/Jd3-eiid-Uw

[11] A. Borrego, J. Latorre, R. Llorens, M. Alcañiz, and E. Noé, "Feasibility of a walking virtual reality system for rehabilitation: objective and subjective parameters," *Journal of NeuroEngineering and Rehabilitation*, vol. 13, p. 68, Aug. 2016, doi: 10.1186/s12984-016-0174-1.

[12] J. E. Cutting and P. M. Vishton, "Chapter 3 - Perceiving Layout and Knowing Distances: The Integration, Relative Potency, and Contextual Use of Different Information about Depth*," in *Perception of Space and Motion*, W. Epstein and S. Rogers, Eds. San Diego: Academic Press, 1995, pp. 69–117. doi: 10.1016/B978-012240530-3/50005-5.

[13] L. Rebenitsch and C. Owen, "Review on cybersickness in applications and visual displays," *Virtual Reality*, vol. 20, no. 2, pp. 101–125, Jun. 2016, doi: 10.1007/s10055-016-0285-9.

[14] G. A. F. Seber, *Multivariate Observations*. John Wiley & Sons, 2009.

[15] D. Webster and O. Celik, "Experimental evaluation of Microsoft Kinect's accuracy and capture rate for stroke rehabilitation applications," in *2014 IEEE Haptics Symposium (HAPTICS)*, Feb. 2014, pp. 455–460. doi: 10.1109/HAPTICS.2014.6775498.

[16] Oliver Kreylos, "Lighthouse tracking examined," *Doc-Ok.org*, May 25, 2016. http://doc-ok.org/?p=1478 (accessed Aug. 30, 2018).

[17] D. C. Niehorster, L. Li, and M. Lappe, "The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research," *Iperception*, vol. 8, no. 3, May 2017, doi: 10.1177/2041669517708205.

[18] M. Slater, A. Steed, and M. Usoh, "The Virtual Treadmill: A Naturalistic Metaphor for Navigation in Immersive Virtual Environments," in *Virtual Environments '95*, Springer, Vienna, 1995, pp. 135–148. doi: 10.1007/978-3-7091-9433-1_12.

[19] B. G. Witmer and M. J. Singer, "Measuring Presence in Virtual Environments: A Presence Questionnaire," *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, pp. 225–240, Jun. 1998, doi: 10.1162/105474698565686.

[20] K. Otte *et al.*, "Accuracy and Reliability of the Kinect Version 2 for Clinical Measurement of Motor Function," *PLOS ONE*, vol. 11, no. 11, Nov. 2016, doi: 10.1371/journal.pone.0166532.

[21] L. F. Ciria *et al.*, "Head movement measurement: An alternative method for posturography studies," *Gait & Posture*, vol. 52, pp. 100–106, Feb. 2017, doi: 10.1016/j.gaitpost.2016.11.020.

[22] W. R. Sherman and A. B. Craig, *Understanding Virtual Reality: Interface, Application, and Design*. Morgan Kaufmann, 2018.

[23] J. Prothero and D. Parker, "A Unified Approach to Presence and Motion Sickness," in *Virtual and Adaptive Environments*, 2003, pp. 47–66.

[24] "i3B UPV." http://www.i3b.upv.es/en/ (accessed Aug. 29, 2018).

[25] A. Febretti *et al.*, "CAVE2: a hybrid reality environment for im-

mersive simulation and information analysis," in *The Engineering Reality of Virtual Reality*, Burlingame, California, United States, Mar. 2013, vol. 8649. doi: 10.1117/12.2005484.

[26] A. Juarez, W. Schonenberg, and C. Bartneck, "Implementing a low-cost CAVE system using the CryEngine2," *Entertainment Computing*, vol. 1, no. 3–4, pp. 157–164, Dec. 2010, doi: 10.1016/j.entcom.2010.10.001.

[27] J. J. LaViola, E. Kruijff, R. P. McMahan, D. Bowman, and I. P. Poupyrev, *3D User Interfaces: Theory and Practice*. Addison-Wesley Professional, 2017.

[28] A. R. Gonçalves, J. E. Muñoz, É. R. Gouveia, M. da S. Cameirão, and S. Bermúdez i Badia, "Effects of prolonged multidimensional fitness training with exergames on the physical exertion levels of older adults," *Vis Comput*, Jul. 2019, doi: 10.1007/s00371-019-01736-0.

[29] J. E. Muñoz, A. Gonçalves, É. Rúbio Gouveia, M. S. Cameirão, and S. Bermúdez i Badia, "Lessons Learned from Gamifying Functional Fitness Training Through Human-Centered Design Methods in Older Adults," *Games for Health Journal*, Aug. 2019, doi: 10.1089/g4h.2018.0028.

[30] F. L. Siena, B. Byrom, P. Watts, and P. Breedon, "Utilising the Intel RealSense Camera for Measuring Health Outcomes in Clinical Research," *J Med Syst*, vol. 42, no. 3, p. 53, Feb. 2018, doi: 10.1007/s10916-018-0905-x.

[31] R. A. Clark, B. F. Mentiplay, E. Hough, and Y. H. Pua, "Three-dimensional cameras and skeleton pose tracking for physical function assessment: A review of uses, validity, current developments and Kinect alternatives," *Gait & Posture*, vol. 68, pp. 193–200, Feb. 2019, doi: 10.1016/j.gaitpost.2018.11.029.

[32] J. A. Albert, V. Owolabi, A. Gebel, C. M. Brahms, U. Granacher, and B. Arnrich, "Evaluation of the Pose Tracking Performance of the Azure Kinect and Kinect v2 for Gait Analysis in Comparison with a Gold Standard: A Pilot Study," *Sensors*, vol. 20, no. 18, Art. no. 18, Jan. 2020, doi: 10.3390/s20185104.

Afonso Gonçalves holds an integrated master's degree in aerospace engineering (2011) from Instituto Superior Técnico (Lisbon, Portugal) and is an Informatics engineering Ph.D. candidate at the University of Madeira (Funchal, Portugal), in the field of Human-Machine Interaction. He has worked at EFACEC SA space activity office as an engineer intern and at the Institute for Systems and Robotics of IST as a research assistant at the computer vision laboratory. He is currently a research assistant at the NeuroRehabLab of Madeira Interactive Technologies Institute. His research focuses on studying and developing exergames to promote physical activity in older age and virtual reality.

Adrián Borrego graduated from the Polytechnic University of Valencia in 2014 in Telecommunications Engineering and he got the Doctorate grade at the Neurorehabilitation and Brain Research Group of the i3b in 2019. His research interests are focused on the use of virtual reality for rehabilitation and assessment, and more specifically, on examining the neurophysiological basis of body-ownership and agency, and on the neuroscience of virtual reality. Adrián has participated in different projects and studies, and has several publications in different areas.

Jorge Latorre graduated from the Polytechnic University of Valencia in 2014 in Telecommunications Engineering and currently, he is a PhD student at the Neurorehabilitation and Brain Research Group of the i3B Institute. His research interests are focused on the use of virtual reality for rehabilitation and assessment, and more specifically, on its application to balance and gait in neurological population using inexpensive and portable devices. Jorge has participated in different projects and studies, and has several publications in different areas.

Roberto Llorens graduated from the Universitat Politècnica de València in 2007 with a major in Telecommunications Engineering. He also earned a Masters in Technology, Communication Systems and Networks in 2011 and got a Doctorate Degree Cum Laude in 2014. His growing interest in applied science led to his association with the i3B Institute in January 2008, where he currently works as a scientific coordinator of the Neurorehabilitation and Brain Research Group, leading several research projects combined with teaching and supervision of several Doctoral Theses and Master Theses. His research interests focus on the neural mechanisms underlying motor, cognitive skills, and embodiment constructs, the study of the neurophysiological substrate of these processes, and the development of experimental neurorehabilitation interventions. Roberto Llorens also carries out his research as a Research Associate in the Neurorehabilitation and Brain Injury Service of NISA Hospitals (Valencia, Spain), and as a Research fellow in the Virtual Environment and Postural Orientation Lab of Temple University (Philadelphia, PA, USA). Roberto Llorens is a member of the Spanish Neurorehabilitation Society and the International Society for Virtual Rehabilitation, and a co-chair of the International Conference on Recent Advances in Neurorehabilitation series.

Sergi Bermúdez i Badia is an Associate Professor at the University of Madeira, senior researcher at the Madeira-ITI and member of the NeuroRehabLab group. He received his MSc. In telecommunications engineering from the Universitat Politècnica de Catalunya (Barcelona) and a Ph.D. in neuroscience from the ETHZ (Zürich). In the past he has also pursued research at the EPFL (Lausanne), the Universitat Pompeu Fabra (Barcelona), and at Carnegie Mellon University (Pittsburgh). His scientific goal is to investigate the underlying neural mechanisms of biological systems and to exploit them using real-world artifacts, with special emphasis in neuro-rehabilitation systems, interactive technologies, and robots. For the past years he has been involved in the development and clinical validation of several motor and cognitive stroke neurorehabilitation systems using interactive technologies such as Virtual Reality, Brain-Computer Interfaces, and haptic interfaces.