IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 20, 2019, accepted December 31, 2019, date of publication January 31, 2020, date of current version February 18, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2970921

A Comparative Study Between Wired and Wireless Virtual Reality Setups

GUILHERME GONÇALVES[1], PEDRO MONTEIRO[3], MIGUEL MELO[3], JOSÉ VASCONCELOS-RAPOSO[2,3], AND MAXIMINO BESSA[1,2]

[1]School of Sciences and Technology, University of Trás-os-Montes and Alto Douro, 5000-801 Vila Real, Portugal
[2]Institute for Systems and Computer Engineering, Technology and Science, 4200-465 Porto, Portugal
[3]School of Human and Social Sciences, University of Trás-os-Montes and Alto Douro, 5000-801 Vila Real, Portugal

Corresponding author: Guilherme Gonçalves (guilhermeg@utad.pt)

This work was supported in part by the European Regional Development Fund (ERDF) through the Operational Programme for Competitiveness and Internationalization-COMPETE 2020 under the PORTUGAL 2020 Partnership Agreement and the Portuguese National Innovation Agency (ANI) as a part of Mobilizing Project CHIC-Cooperative Holistic View on Internet and Content under Grant 24498, and in part by the CHIC-Cooperative Holistic View on Internet and Content, financed the European Regional Development Fund (ERDF) through COMPETE2020-the Operational Programme for Competitiveness and Internationalization (OPCI), under Grant 24498.

ABSTRACT Virtual Reality (VR) through head-mounted displays (HMDs) can be delivered via multiple setups such as smartphones, standalone VR or VR Workstations. The VR Workstation setup delivers the best performance of them all; however, as a drawback up until recently, it required cables to power up the VR equipment. The introduction of wireless solutions for VR Workstations came to solve one of the disadvantages of this setup. However, the impact of the wireless solution versus the HMD cables was not yet properly investigated. In this paper, we study the impact of using a wired vs wireless HMD on Presence, Cybersickness, and Game Experience. We conducted a quasi-experimental between-subjects study with 68 participants assigned to the following three groups that were balanced regarding gender and sample size: *Cable* (participants used a wired HMD), *Cable* + *Help* (a researcher assisted the participants with the HMD cable during the experience to reduce the participants' awareness of it), and *Wireless* (untethered HMD). Results showed no significant differences in presence and cybersickness. The game experience was significantly different, with *Cable* + *Help* performing better than *Cable* and *Wireless*. We conclude that sense of presence using wireless solutions is equated to wired HMD solutions.

INDEX TERMS Virtual Reality, immersion, presence, Cybersickness, game experience, wireless, head-mounted display.

I. INTRODUCTION

Virtual Reality (VR) has been evolving since the prototypes [1]–[3] into the widespread success that it is today. Up until recently, VR Headsets or Head-Mounted Displays (HMD) were wired, usually to computers, to ensure enough computational capability so the VR unit can properly deliver the virtual experience (VR Workstation). One fact is that the presence of cables is not of much importance if users would experience VR while sitting or standing without physical movements. However, the evolution of VR applications is towards experiences that require freedom of movements in 6-DOF (degrees of freedom) over a wide tracking area. In such a scenario, wireless solutions would be preferable since the HMD cable can compromise the VR experience by, for instance, making users trip over it or getting wrapped.

The associate editor coordinating the review of this manuscript and approving it for publication was Noor Zaman.

A. PRESENCE

The concept of presence has been defined differently throughout the literature [4]–[18]. However, a widely accepted definition of Presence and one which we follow in this work is Slater's definition [14]: presence is a state of consciousness, a psychological sense of being in the virtual environment (VE). This is considered one of the most important aspects of VR — the possibility for users to develop an intense sense of Presence. This sense of Presence will result in users behaving more realistically in the virtual environments [14], [19]–[21]. The measurement of presence has been used in several works to evaluate VR applications. The search for the knowledge of what affects the presence and how is presence developed is one of the most researched topics in this field [4], [5], [9], [16].

B. IMMERSION

The term immersion is often used alongside presence as being the same thing. In this work, we make the distinction between presence and immersion. Immersion is the level to which the technology can recreate a rich and credible virtual experience by successfully shutting out reality [14]. Immersion is objective, unlike Presence. A more immersive system offers better conditions for users to feel more present. Following this line of thought, the cable is an element that can distract users, and remind them of their surrounding reality. Therefore, by providing a wireless experience, we are raising the immersion of the system and thus, the probability of users feeling more present.

C. CYBERSICKNESS

Complementary to Presence and Game Experience, Cybersickness is an important factor to take into account. In previous user studies, we have observed that using large areas and real walking leads users to get wrapped in the HMD cables by the constant turning around, users would often turn 360° degrees to unwrap themselves from the cables. This constant turning may cause Cybersickness symptoms. These are motion sickness like symptoms that occur in VR, usually when the vestibular and visual systems conflict with each other [22], [23]. For example, if we are looking down reading a book while traveling on a bus, our visual system will not pick up cues that we are moving while our vestibular system will sense that we are. The conflict between the visual and vestibular will result in motion sickness. A similar phenomena can happen in VR, where we sense our body and head movement, but the tracking or computer cannot process correct visual stimuli in time (lag). Some of the symptoms that may arise from that are nausea, headaches, ocular discomfort, and disorientation.

D. GAME EXPERIENCE

Breaks in Presence and the constant reminding that users are acting in a virtual environment could also influence Game Experience. According to the GameFlow model [24], immersion is one of the elements that contribute to player enjoyment in games. An immersed player would ''become less aware of their surroundings, less self-aware and less worried about everyday life or self''. Here, we can see how the constant interference of HMD cables can distract users out of the virtual experience and back to reality. Concentration could also be impacted, as players ''should not be distracted from tasks that they want/need to concentrate on'' and where the game should ''quickly grab the player's attention and maintain their focus throughout the game'' between other criteria. We thus suspect that the VR wireless solution will improve Game Experience by reducing possible distractions and allowing players to maintain a better focus on what they are doing.

E. HOW CABLES IMPACT THE VIRTUAL EXPERIENCE

From previous studies, we have observed that the cable that connects the HMD to the computer was usually an ''anchor point'' to reality. Participants often stated at the end of the experience that sometimes the cable reminded them that they were in a virtual world. We also observed that some users were making 360° turns and other movements to avoid getting wrapped in the cables. We must note that this only happened in virtual experiences where participants used real walking metaphor (please refer to [25] for more details regarding real walking metaphor). We theorize that the cable may cause consistent breaks in Presence (events that remind users that they are in a virtual environment, breaking the illusion of ''being there'' [26], [27]).

In the literature, several studies also mention cables as being a potential problem. Davis *et al.* [23] discuss that general ergonomics need to be considered and refers to HMD cables as capable of distracting users from the experience.

Meehan *et al.* [28] pointed out that: ''Additionally, we must eliminate the cables that tether subjects to the monitoring, tracking, and rendering equipment. Our subjects reported this encumbrance as the greatest cause of breaks in Presence.''

Rizzo and Kim [29] comment that: ''Wires constrain interaction, both mentally and physically, and complex motion can result in the user getting tangled in wires and cables that limit usability and could create safety hazards.''

Slater and Steed [30] studied the mental transition of users between the virtual and real world. Participants were asked to point out the causes of this transition. Between several causes, participants pointed out that ''Becoming aware of cable wrapped around the foot.'', ''The cable brushing against my legs.'', and ''Trapped in wires.'' led them to transition from virtual environment to the reality.

Garau *et al.* [27] investigated breaks in Presence using a CAVE (Cave Automatic Virtual Environment). Authors stated that, among others, environmental factors related to the apparatus, contributed to breaks in Presence as participants found the 3D stereoscopic glasses uncomfortable. They follow up with a citation from a participant stating that ''Maybe the sensation of this thing on the glasses, because I'm not very comfortable. The worry that I would step on the cable and break your equipment''.

To mitigate the effects of a wired solution, the retractable cable management solutions decrease the weight of the cables and avoid that the cable gets wrapped around the user. However, in these solutions, users can still pinpoint their location in the real world relative to the cable. Also, they require an already installed set of ''hooks'' in the ceiling that are less convenient if we want to change the VR setup to another place. Moreover, it is only possible to use this type of solution if we have a closed area with a ceiling at an acceptable height.

F. ADVANTAGES AND DISADVANTAGES OF VR WIRELESS SOLUTION

Wireless solutions can solve the problems that cables bring, but in contrast, they are not free of disadvantages.

VR wireless solutions are usually based on VR smartphone headsets or dedicated standalone VR equipment. However, due to their reduced computational capability when compared to a VR Workstation, these solutions tend to have lower performance (which can result in lower simulation quality). Also, VR smartphones headsets use the built-in accelerometers and gyroscopes of the smartphones to track the head, which could be unreliable and only provide 3-DOF tracking. Only recently, wireless adapters for VR Workstations were made available and brought the possibility of using a VR Workstation with high-performance HMDs to deliver wireless VR experiences.

Due to technological limitations, some lag or inconsistencies could happen while transmitting a video signal at high framerates (near 90 frames per second) and high resolution (1080×1200 pixels per eye). A study was conducted in this regard, using the same equipment used in this study (TPCAST) [31]. Authors stated that freezes in video playback were uncommon and they did not notice freezes during regular usage. They also reported a frame-rate of near 90fps, which is the refresh rate of the HTC Vive.

Although the world is moving towards tetherless solutions, state of the art equipment with very high resolutions, refresh rates and other specifications will still need tethered connections as the time to market of new state-of-art wireless solutions is slow. Some high-end HMDs are still needing cables because of their throughput requirements.

G. CONTRIBUTION

To the best of our knowledge, there are still no studies that focus on the benefits of wireless VR adaptors in interactive VR applications that require real-walking to navigate in demanding virtual environments. Therefore, in this work we aim to create knowledge about how much of an advantage the wireless solution can be against the standard wired HMD by studying Presence, Cybersickness and Game Experience in a between-subjects controlled study.

We hypothesize that the VR wireless solution will improve both Presence and Game Experience because the absence of cables will increase the system immersion, resulting in users to be less aware of the real world, less distracted and less worried about tripping over the cables.

Regarding Cybersickness, a constant turning around due to the cables could raise the probability of participants feeling these symptoms. However, we believe that this should not be significant to the point where removing the HMD cables from the experience would result in lower significantly lower Cybersickness.

Thus, we propose the following hypotheses:

- H1: Presence will be higher in the VR wireless solution.
- H2: The VR wireless solution will not influence Cybersickness.
- H3: Game experience will be higher in the VR wireless solution.

II. METHODS

A quasi-experimental cross-sectional study of comparative nature following a between-group design was conducted to investigate the impact of the absence of HMD cables on Presence, Game Experience and Cybersickness.

A. SAMPLE

We used a non-probabilistic sampling technique, namely, convenience sampling. The sample consisted of 68 participants (40 males and 28 females) aged between 16 and 49 ($M = 21.43$, $SD = 4.773$), mostly university students. The participants were divided between three groups (see subsection II-B), with 19 participants assigned to the first group, 23 to the second and 26 to the third group (evenly balanced between genders). The assignment of the participants to each group was made ensuring that sample size and gender was balanced between conditions. All participants were naive to the conditions of the experiment.

B. VARIABLES

We considered the VR setup as the independent variable with three levels:

1) `Cable` ($N = 19$): HMD with the original cable that runs from the headset to the computer
2) `Cable + Help` ($N = 23$): HMD with the original cable and with a research team member managing the cable to minimize its interference on the virtual experience.
3) `Wireless` ($N = 26$): HMD using the TPCAST® wireless adapter [32] and power-bank. In this condition, participants can move freely without the interference of cables.

As dependent variables, the following were considered:

- Presence and its subscales (Spatial Presence, Experienced Realism, Involvement): The illusion of being in the virtual environment as being real. Presence was measured through the IPQp questionnaire [33].
- Cybersickness and its subscales (Nausea, Oculomotor discomfort, Disorientation): Motion sickness-like symptoms that can occur when visual and vestibular system enter in conflict. Cybersickness was measured through the SSQ questionnaire [34].
- Game Experience and its subscales (usability/playability, narratives, play engrossment, enjoyment, creative freedom, audio aesthetics, personal gratification, and visual aesthetics): The overall satisfaction players get from playing the game. Game experience was measured through the GUESS questionnaire [35].

C. INSTRUMENTS

We collected data about Presence, Cybersickness and Game Experience through questionnaires, complemented with direct observation of how users behave during the experience and through a debriefing session after completing the questionnaires. As for the Presence, we used the validated

Portuguese version of the Igroup Presence Questionnaire (IPQp) [33], [36]. The questionnaire uses a 5-point Likert scale with 14 items that results in the following subscales: spatial Presence (the feeling of being physically present in the virtual environment), experienced realism (the subjective experience of realism), involvement (the attention that is given to the environment and the level of involvement experienced) and Presence (the global sense of Presence).

Cybersickness was evaluated using the Portuguese translated version of the Simulator Sickness Questionnaire (SSQ) [34]. It's composed of 16 items corresponding to various symptoms that are classified as none, slight, moderate or severe. The questionnaire includes the following subscales: nausea (nausea, salivation, burping, stomach awareness), oculomotor discomfort (eye strain, difficulty focusing, blurry vision), disorientation (vertigo and dizziness) and Cybersickness (global Cybersickness).

For the evaluation of Game Experience, we used the translated Portuguese version of the Game User Experience Satisfaction Scale (GUESS) [35]. This questionnaire has 55 questions, on a 7-point Likert scale regarding 9 factors of the gaming experience: usability/playability, narratives, play engrossment, enjoyment, creative freedom, audio aesthetics, personal gratification, social connectivity, and visual aesthetics. Because there was no social connectivity, this factor was removed from the analysis.

D. MATERIALS

In this section, we describe the virtual reality game used as well as the immersive system apparatus. As such, we divided the materials into two subsections: software and hardware.

E. SOFTWARE

We used a VR game developed by the research team using Unity® 2017, named ''Illusions''. The game aimed for an immersive experience, using real-walking [25] and so it presents a dark and scary ambient, depicting the interior of an abandoned hospital (1). The narrative focuses on the mystery of why is the player in that place and who he is. While progressing through the game the player learns that he/she is a schizophrenic patient. The game ends in a white cushioned room where the player realizes that it was all a hallucination and he/she never left the room.

The locomotion is achieved by using a real-walking metaphor in an area of 4×4 meters. The level design was done in such a way that participants will not need to turn 180° degrees to continue walking through the game. Players will subtly walk in circles, giving the sensation that the VE is bigger than it is, and disorienting them regarding their orientation and localization in the real world. The level design is also symmetric, meaning that the player, when unlocking the door, can go left or right towards the next level with the same outcomes (Fig. 2).

There are three floors, each one corresponding to one level. The player starts in the first level inside a room where he must find a key to unlock a door which will give the player access to a corridor. From there, the player can move to the next level by walking towards one of the two stairs, one on each side. Because the participants cannot physically climb stairs, when the player reaches the stair's icon, he is teleported to the next level. In the second level, the player has to find a new key to unlock another door, which will give them access to a ''pit room''. Here, the player reaches one of the two doors available by leaning on the edge of the room and side-walk towards the door. When opened, the player will be teleported to the next level. Again, he/she has to find a new key. To do so, the player has to find and interpret a code to open a safe. Inside the safe, lies one key to unlock the door, another to unlock a fuse box, a medical record sheet and photos of the game narrative. The player has then to open the door, catch two fuses, each one in the far side of the corridor, and insert them into the fuse box. This will power two elevators situated in the corridor which the player has to enter and where the game will finish. The game requires the player to explore the scene to find the keys. This involves a lot of movement, turning back and forth.

FIGURE 1. Screen shot of level 2 (illustrative example of the virtual environment, better visualised on screen).

F. HARDWARE

The VR game was played on a Windows® computer with the following specifications: CPU Intel® Core™ i7-5820K @ 3.30GHz, 32GB RAM, Nvidia® Geforce® GTX 1080.

For the wired VR setup, we used the HTC® Vive™ system, which has one cable that runs from the HMD to the computer. A cable extension was used to avoid participants running out of cable when reaching the far side of the play area.

For the wireless solution, we used the TPCAST®, a wireless adapter for the HTC® Vive™. The wireless solution requires a power bank to deliver power to the adapter and HMD, which was in a bag secured to the participants' belt running a cable towards the HMD thought the back. The research team tested this wireless solution previously to verify its capabilities and to fine-tune it to avoid possible signal interference. From what we experienced, the VR wireless solution proved to be capable of handling all the data without significant problems. Differences in image quality were indistinguishable between wired and wireless. However, the

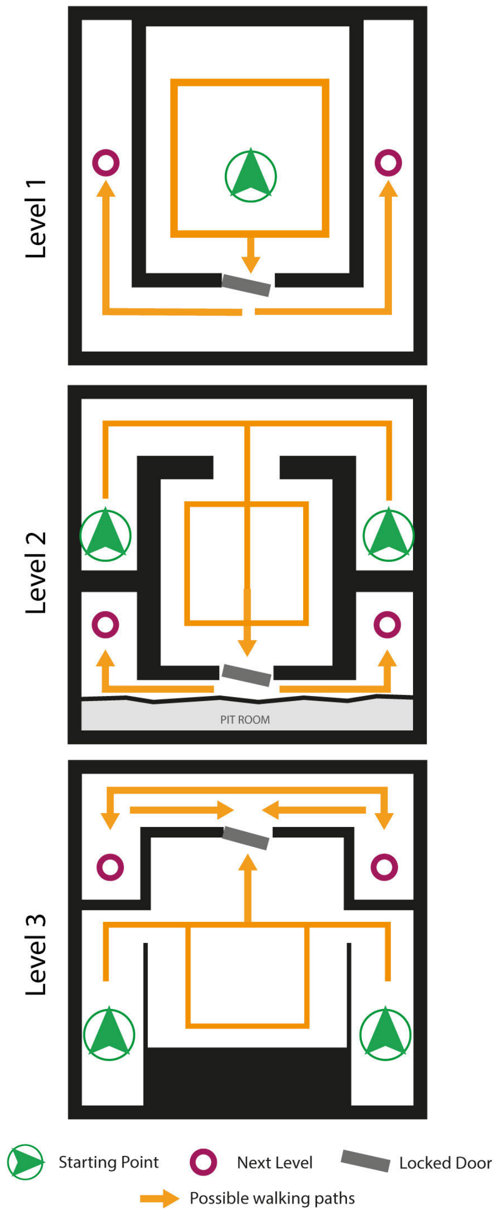

FIGURE 2. Levels layouts.

image quality would degrade if the line of sight between the transmitter and receiver was blocked. To avoid this, the transmitter was placed near the ceiling to cover the full playing area and with a direct line of sight to the receiver. The research team did not notice latency or inconsistencies while using this wireless solution.

To deliver the audio, we used active noise-cancelling headphones connected to the HTC® Vive™ 3.5mm jack.

G. PROCEDURE

Participants performed the experiment at a specialized Virtual Reality Laboratory. The laboratory's experimental room allows the full control of variables such as light, temperature, ambient air circulation, as well as, soundproof walls and doors. As such, participants performed the experiments under the same environmental conditions.

FIGURE 3. Participant performing the experience with HMD cables.

Before beginning the experiment, participants filled a consent form and a brief questionnaire with their age and gender. Participants wore the HMD and headphones, and in the wireless condition, the power-bank secured to their waist with the help of a researcher to ensure proper equipment placement and participant's comfort. All participants started the virtual experiment with the same orientation and position in the room. Subjects were not aware of what was being studied.

In the `Cable` condition, there was no help in managing the HMD cables, so participants would have to avoid wrapping themselves on the cable (Fig. 3). In the `Cable + Help` condition, a researcher would try to minimize the player awareness of the cable. This was done by strategically moving the cable without the participants' knowledge. In the `Wireless` condition, players would move freely through the game due to the non-existence of a cable between the computer and HMD. It should be noted that regardless of the condition, there was always a researcher to provide physical support if participants would leave the play area (although limits were defined in the virtual environment), lose balance, or trip over the cable (when applicable).

There was no time limit: the virtual experiment ended when participants reached the end of the game. Right after ending the virtual experiment, participants were asked to complete the IPQp, SSQ, and GUESS questionnaires and lastly an observations field to add optional additional information. In the end, we debriefed the participants to assess what they thought about the experience and any additional observations they might want to share with the goal of verifying if there were comments made regarding the existence of cables.

III. RESULTS

All statistical procedures were performed using the IBM® SPSS® 24 software. A preliminary analysis of the data was conducted to verify outliers and normal distribution. A total of sixteen outliers were identified (through visual inspection of box plots) and removed. The distribution of participants

TABLE 1. IPQp subscale score means, standard deviations, and ANOVA statistical test results for each presence subscale on each condition. Subscale means range from 1 to 5 with higher values being better.

IPQp Subscale	Cable		Cable + Help		Wireless		p	η_p^2	OP
	M	SD	M	SD	M	SD			
Spatial Presence	3.740	0.375	3.810	0.369	3.894	0.270	0.369	0.040	0.217
Experienced Realism	3.375	0.606	3.660	0.830	3.273	0.645	0.259	0.054	0.284
Involvement	3.688	0.798	3.982	0.495	3.966	0.687	0.385	0.038	0.210
Presence	3.621	0.375	3.816	0.361	3.737	0.250	0.254	0.054	0.288

TABLE 2. SSQ subscale score means, standard deviations for each experiment condition, and Kruskal-Wallis H statistical test results. Scores range from 0 to 201, 160, 293 and 2437 (nausea, oculomotor discomfort, disorientation, and cybersickness respectively). Lower values are better.

SSQ Subscale	Cable		Cable + Help		Wireless		$\chi^2(2)$	p
	M	SD	M	SD	M	SD		
Nausea	11.046	12.010	11.199	17.650	10.641	14.106	0.429	0.951
Ocular. Discomfort	9.974	12.392	10.546	12.876	8.746	12.070	0.295	0.791
Disorientation	13.920	16.073	15.130	17.763	14.991	23.598	0.335	0.625
Cybersickness	12.992	13.156	13.659	16.091	12.515	15.971	0.218	0.820

after the removal of outliers were the following: `Cable` ($N = 16$); `Cable + Help` ($N = 14$); `Wireless` ($N = 22$). The data from 52 participants (27 male and 25 female) was analyzed.

All the dependent variables regarding presence and game experienced were normally distributed ($|Skewness| < 2$ and $|Kurtosis| < 2$). Therefore, parametric statistics were used, namely Analysis of variance (ANOVA). The Levene test was performed to evaluate the ANOVA homogeneity assumption. The subscales usability/playability, Enjoyment, Audio Aesthetics, Visual Aesthetics, and Final Score violated the homogeneity assumption, thus, for these subscales, a Welch ANOVA was performed.

Some cybersickness scores did not follow a normal distribution, thus non-parametric statistical tests were used to compare the different groups, namely the Kruskal-Wallis H test.

A. PRESENCE

No statistically significant differences were found between the experimental groups for Spatial Presence ($F(2, 49) = 1.017; p = 0.369; \eta_p^2 = 0.040; OP = 0.217$), Experienced Realism ($F(2, 49) = 1.388; p = 0.259; \eta_p^2 = 0.054; OP = 0.284$), Involvement ($F(2, 49) = 0.973; p = 0.385; \eta_p^2 = 0.038; OP = 0.210$) and overall Presence ($F(2, 49) = 1.411; p = 0.254; \eta_p^2 = 0.054; OP = 0.288$) as shown in the Table 1.

B. CYBERSICKNESS

As assessed by visual inspection of boxplots, distributions of Cybersickness scores for all its subscales were similar between the groups. No statistically significant differences for Nausea ($\chi^2(2) = 0.100, p = 0.951$), Ocular Discomfort ($\chi^2(2) = 0.469, p = 0.791$), Disorientation ($\chi^2(2) = 0.939, p = 0.625$) and overall Cybersickness ($\chi^2(2) = 0.396, p = 0.820$) were found between the three groups (Table 2).

C. GAME EXPERIENCE

Statistically significant differences were found for Creative Freedom ($F(2, 49) = 6.548; p = 0.003; \eta_p^2 = 0.211; OP = 0.891$), Audio Aesthetics ($F(2, 29.116) = 9.000; p = 0.001$), Visual Aesthetics ($F(2, 30.537) = 4.332; p = 0.022$), and Final Score ($F(2, 30.003) = 8.993; p = 0.001$) (Table 3).

To identify the conditions where the differences lie, we followed up with a Bonferroni post-hoc analysis for the scales with homogeneity of variance. For the rest, Games-Howell post-hoc was used.

The differences in the Creative Freedom scale lied between the conditions: `Cable` – `Cable + Help` ($p = 0.021$) and `Cable + Help` – `Wireless` ($p = 0.003$). Creative freedom was significantly higher in `Cable + Help` ($M = 5.524$, $SD = 0.517$) than `Cable` ($M = 4.783$, $SD = 0.764$) and `Wireless` ($M = 4.672$, $SD = 0.787$) conditions.

Audio Aesthetics scores were higher ($p = 0.001$) in `Cable + Help` ($M = 5.893$, $SD = 0.189$) than in the `Wireless` condition ($M = 5.474$, $SD = 0.407$).

Visual Aesthetics scores were higher ($p = 0.016$) in `Cable + Help` ($M = 5.762$, $SD = 0.242$) than in `Wireless` ($M = 5.439$, $SD = 0.416$) condition.

Final score was statistically different between: `Cable` – `Cable + Help` ($p = 0.007$) and `Cable + Help` – `Wireless` ($p = 0.004$). Scores were higher in `Cable`

+ Help ($M = 44.044$, $SD = 1.605$) than in Cable ($M = 40.657$, $SD = 3.614$) and Wireless ($M = 41.714$, $SD = 2.442$) conditions.

D. ANECDOTAL EVIDENCE

Although no significant difference was found, we observed different user behaviors towards the Presence of the HMD cable. When participants sensed they were getting trapped in the cables by a constant turning around, they would purposely turn the other way around (almost doing a 360° rotation) to get rid of the cable. Some also used their hands and arms to move away from the cable from their path to make sure they would not trip over it.

Some participants stated in the observations field of the questionnaire that to improve the virtual experience, the cable would have to be removed. Some of the comments given by the Cable condition participants were: "If possible, reduce the cables of the VR setup, the fear of tripping and falling over them is big and prevents us from totally losing consciousness of the real world", "The HMD cable perturbed a little", "A headset without cables would help to improve the experience", and "The cable was always present and cause us to react to the real world". This suggests that some users did notice the interference of the cable enough to suggest removing it, however, its impact in the overall Presence, Cybersickness, and Game Experience was not significant.

IV. DISCUSSION

In this section, results are discussed regarding our hypotheses and their implications in the field. We divided the discussion to focus Presence, Cybersickness and Game experience individually.

A. PRESENCE ANALYSIS

We suggested in H1 that Presence scores would be higher in the VR wireless solution. Such was due to the wireless solution offering a more immersive system by allowing increased freedom of movement without an interfering element connecting users to the real world. However, Presence scores led us to not accept this hypothesis. Even though users noticed the cable (as observed in their behavior and comments in the questionnaire), its absence did not cause a significant difference in Presence scores.

During the wireless condition, we noticed some instability in the wireless connection in a few participants. Some times the HMD would lose image and sound during a short period of time (around three seconds). However, these occurrences were rare. This seemed to happen randomly, despite our best efforts to minimize interference of the signal in the room. These "blackouts" can be considered as breaks in presence. Garau *et al.* [27] studied how whiteouts affected the subject's transition from VR back to reality. The authors blanked out the CAVE four times throughout the experiment, each time for two seconds. These induced whiteouts were very similar to the blackouts some participants experienced in this work. In their work participants noticed and perceived the whiteouts as breaks in presence. The first whiteout was considered the most impactful, with the following being less pronounced. Participants were able to recover their sense of presence after the breaks of presence. However, the time needed to recover was longer for each successive whiteout.

Although the blackouts might have influenced Presence, we argue that they were not the main cause for the lack of significant differences as they occurred rarely for brief seconds on an experience that took approximately 15 minutes. So there was time for users, that experienced the blackout, to recover their sense of Presence.

Overall, we observed the HMD cable interfering in the experience more often than the wireless solution did when it momentarily failed. Such leads us to believe that the wireless solution still should provide a better experience than using wired solutions.

B. CYBERSICKNESS ANALYSIS

It was expected that the Wireless condition would not influence Cybersickness scores in H2. This was due to a previous study [31] where it was concluded that the TPCAST was able to provide the visual stimuli without freezes and also due to preliminary tests the research team did, where no lag between the user input and the corresponding output of the stimuli to the HMD was noticed. The results showed no significant differences between conditions which suggest that wireless solutions could be used without any additional Cybersickness interference.

C. GAME EXPERIENCE ANALYSIS

From a Game Experience perspective, we aimed to study if playing without HMD cables would be significantly better as we hypothesized in H3. The results demonstrated that Creative Freedom, Audio Aesthetics, Visual Aesthetics, and Final scores were higher in the Cable + Help condition. Such results indicate that it is better for the participant game experience to have someone to manage the cables than simply leaving the users to manage themselves. Such could be easily justified by the fact that in Cable + Help condition, users are a lot less aware of the cable and can better focus on the experience itself.

Subjects were not aware of the fact that a researcher would help them with the cable. Although, there is the possibility that during the experience, knowing that there were cables and they were not interfering, subjects might have started to assume someone was helping and maybe started to feel more "safe", worrying less with their real surroundings, focusing more attention in the VR. However, no participants commented on such.

Wireless was expected to improve over the Cable+Help. However, results indicated that such was not the case. A similar justification for the differences between Cable and Cable + Help might apply. Subjects might felt more insecure by using a wireless solution because they were not aware if someone was watching over them. Such could cause subjects to allocate part of their attention to the real

TABLE 3. GUESS subscale score means and standard deviations, significance level, and ANOVA statistical test results for each game experience subscale on each condition. For Welch's ANOVA only the significance level is presented. Subscales range from 0 to 6 with higher values being better. The final score is the sum of all subscales.

GUESS Subscale	Cable		Cable + Help		Wireless		p	η_p^2	OP
	M	SD	M	SD	M	SD			
Usability/playability	4.846	0.727	5.182	0.547	4.966	0.399	0.323		
Narratives	4.504	0.978	5.089	0.596	4.952	0.612	0.078	0.099	0.508
Play Engrossment	4.872	0.520	5.233	0.381	5.059	0.403	0.088	0.095	0.488
Enjoyment	5.250	0.956	5.814	0.266	5.727	0.347	0.093		
Creative Freedom	4.783	0.764	5.524	0.517	4.672	0.787	0.003	0.211	0.891
Audio Aesthetics	5.641	0.570	5.893	0.189	5.474	0.407	0.001		
Personal Gratification	5.179	0.595	5.548	0.405	5.424	0.511	0.140	0.077	0.402
Visual Aesthetics	5.583	0.509	5.762	0.242	5.439	0.416	0.022		
Final Score	40.657	3.614	44.044	1.605	41.714	2.442	0.001		

environment to avoid damaging the equipment by colliding with real objects. Previous studies in the literature [27], [29] stated some concerns about subjects possibly damaging experimental apparatus.

However, if such was the reason for the `Cable + Help` outperforming the other conditions, then presence scores should also have reflected it. More studies are needed to verify the proposed justification and to verify why the game experience was significantly different and presence was not.

V. CONCLUSION

In this work, we aimed to study the impact of HMD cables in the Presence, Cybersickness and Game Experience by comparing three conditions (*Cable*, *Cable + Help*, and *Wireless*) using a VR game focused in freedom of movement that makes use of real walking as navigation metaphor.

Theoretically, the less the impact of the cable, the more immersive the VR system is, and the better are the conditions for subjects to feel more present and to have better game experience. The results showed that there were no differences in Presence and Cybersickness, but some subscales as well as overall score of Game Experience were found to be higher in `Cable + Help` than in other conditions.

The results indicated that the sense of presence on wireless solution is equated to wired ones. As such, researchers could compare this metric between their studies using wireless solutions against wired HMD. For example, in terms of Presence, researchers can discuss that the cause of the improvement was not the wireless setup but another variable that was being studied.

The wireless solution did not invoke more cybersickness symptoms than in wired HMD. This led us to conclude that the wireless solution is capable to receive the user input and deliver the correct feedback avoiding possible sensory conflicts. Therefore, Presence and Game Experience scores could not have been influenced by such symptoms.

Results indicated that Game Experience was rated significantly better in the `Cable + Help`. Although more studies are needed to confirm this, subjects might have realized that a researcher was present in the experimental room watching over their movements, which could have increased the sense of security of subjects. Such could have led them to worry less about their real surroundings and concentrate their attention in the virtual reality game.

Based on the anecdotal evidence, the wireless solution presents an advantage towards the standard HMD setup. Users are less likely to trip or get wrapped up in the cables, as well as researchers don't have the need to supervise participants so closely to ensure they would not fall or disconnect the equipment by stretching the cables. However, signal interference presents a problem that has to be solved and controlled before fully adopting wireless solutions.

Additional studies are needed to verify the extent to which participants were aware of the fact that someone was helping with the cables in the `Cable + Help` condition and evaluate how worried participants were about the cables in the conditions featuring tethered HMD. User performance could also be taken into account in future work to verify how well users perform between conditions. To improve this study furthermore, new wireless modules and HMDs should be taken into account and evaluated as they are released to the market, to verify what improvement they may bring.

REFERENCES

[1] M. L. Heilig, "Sensorama simulator," Google Patents US 3 050 870 A, Jan. 10, 1961. [Online]. Available: https://www.google.com/patents/US3050870 and http://www.google.com/patents/US3050870

[2] I. E. Sutherland and I. E. Sutherland, "The ultimate display," in *Proc. IFIP Congr.*, vol. 2, 1965, pp. 506–508. [Online]. Available: http://citeseer.ist.psu.edu/viewdoc/summary?doi=10.1.1.136.3720

[3] J. E. A. Link, "Trainer for aviators," Google Patents US 2 099 857 A, Aug. 14, 1936. [Online]. Available: https://www.google.com/patents/US2099857

[4] H. Q. Dinh, N. Walker, L. F. Hodges, C. Song, and A. Kobayashi, "Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments," in *Proc. IEEE Comput. Soc.*, Jan. 1999, pp. 222–228. [Online]. Available: http://ieeexplore.ieee.org/document/756955/

[5] R. M. Baños, C. Botella, M. Alcañiz, V. Liaño, B. Guerrero, and B. Rey, "Immersion and emotion: Their impact on the sense of presence," *CyberPsychol. Behav.*, vol. 7, no. 6, pp. 734–741, Dec. 2004. [Online]. Available: http://www.liebertonline.com/doi/abs/10.1089/cpb.2004.7.734

[6] D. Narciso, M. Bessa, M. Melo, A. Coelho, and J. Vasconcelos-Raposo, "Immersive 360° video user experience: Impact of different variables in the sense of presence and cybersickness," *Univ Access Inf Soc*, vol. 18, no. 1, pp. 77–87, Mar. 2019. [Online]. Available: http://link.springer.com/10.1007/s10209-017-0581-5

[7] M. V. Sanchez-Vives and M. Slater, "From presence to consciousness through virtual reality," *Nat. Rev. Neurosci.*, vol. 6, no. 4, pp. 332–339, Apr. 2005. [Online]. Available: http://www.nature.com/articles/nrn1651

[8] R. Skarbez, F. P. Brooks, Jr., and M. C. Whitton, "A survey of presence and related concepts," *CSURACM Comput. Surv.*, vol. 50, no. 6, pp. 1–39, Nov. 2017. [Online]. Available: http://dl.acm.org/citation.cfm?doid=3161158.3134301

[9] J. J. W. Lin, H. B. L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness, "Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment," in *Proc. IEEE Virtual Reality*, Mar. 2002, pp. 164–171.

[10] M. Melo, J. Vasconcelos-Raposo, and M. Bessa, "Presence and cybersickness in immersive content: Effects of content type, exposure time and gender," *Comput. Graph.*, vol. 71, pp. 159–165, Apr. 2018. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0097849317301917

[11] M. Slater, J. Mccarthy, and F. Maringelli, "The influence of body movement on subjective presence in virtual environments," *Hum. Factors*, vol. 40, no. 3, pp. 469–477, Sep. 1998. [Online]. Available: http://journals.sagepub.com/doi/10.1518/001872098779591368

[12] A. Felnhofer, O. D. Kothgassner, L. Beutl, H. Hlavacs, and I. Kryspin-Exner, "Is virtual reality made for men only? Exploring gender differences in the sense of presence," in *Proc. Int. Soc. Presence Res.*, 2012, pp. 103–112.

[13] G. Goncalves, M. Melo, and M. Bessa, "Virtual reality games: A study about the level of interaction vs. Narrative and the gender in presence and cybersickness," in *Proc. Int. Conf. Graph. Interact. (ICGI)*, Nov. 2018. [Online]. Available: https://ieeexplore.ieee.org/document/8602686/

[14] M. Slater and S. Wilbur, "A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments," *Presence, Teleoperators Virtual Environ.*, vol. 6, no. 6, pp. 603–616, Dec. 1997. [Online]. Available: http://www.mitpressjournals.org/doi/10.1162/pres.1997.6.6.603

[15] P. Fuchs, G. Moreau, and P. Guitton, Eds., *Virtual Reality: Concepts and Technologies*. Boca Raton, FL, USA: CRC Press, 2011.

[16] P. Bouvier, "The five pillars of presence: Guidelines to reach presence," in *Proceedings of Presence*, A. Spagnolli and L. Gamberini, Eds. Padua, Italy: CLEUP, 2008, pp. 246–249.

[17] W. IJsselsteijn and G. Riva, "Being there: The experience of presence in mediated environments," in *Studies in New Technologies and Practices in Communication* (Being there: Concepts, Effects and Measurements of User Presence in Synthetic Environments), G. Riva, F. Davide, and W. A. IJsselsteijn, Eds. Amsterdam, The Netherlands: IOS Press, 2003, pp. 3–16.

[18] M. Lombard and T. Ditton, "At the heart of it all: The concept of presence," *J. Comput.-Mediated Commun.*, vol. 3, no. 2, Aug. 2010. [Online]. Available: https://academic.oup.com/jcmc/article/4080403

[19] M. Slater, "Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments," *Philos. Trans. Roy. Soc. B*, vol. 364, no. 1535, pp. 3549–3557, Dec. 2009. [Online]. Available: http://rstb.royalsocietypublishing.org/cgi/doi/10.1098/rstb.2009.0138

[20] M. Bessa, M. Melo, A. Augusto De Sousa, and J. Vasconcelos-Raposo, "The effects of body position on Reflexive Motor Acts and the sense of presence in virtual environments," *Comput. Graph.*, vol. 71, pp. 35–41, Apr. 2018. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0097849317301863

[21] J. Fröhlich and I. Wachsmuth, "The visual, the auditory and the haptic—A user study on combining modalities in virtual worlds," in *Proc. Int. Conf. Virtual, Augmented Mixed Reality*. Berlin, Germany: Springer, 2013, pp. 159–168.

[22] J. J. Laviola, "A discussion of cybersickness in virtual environments," *SIGCHI Bull.*, vol. 32, no. 1, pp. 47–56, Jan. 2000. [Online]. Available: http://portal.acm.org/citation.cfm?doid=333329.333344

[23] S. Davis, K. Nesbitt, and E. Nalivaiko, *A Systematic Review of Cybersickness*. New York, NY, USA: ACM Press, 2014, pp. 1–9. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2677758.2677780

[24] P. Sweetser and P. Wyeth, "GameFlow: A model for evaluating player enjoyment in games," *Comput. Entertainment*, vol. 3, no. 3, p. 3, 2005. [Online]. Available: http://portal.acm.org/citation.cfm?doid=1077246.1077253

[25] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks, *Walking >Walking-in-Place >Flying, in Virtual Environments*. New York, NY, USA: ACM Press, 1999, pp. 359–364. [Online]. Available: http://portal.acm.org/citation.cfm?doid=311535.311589

[26] M. Slater and A. Steed, "A Virtual Presence Counter," *Presence: Teleoperators Virtual Environments*, vol. 9, no. 5, pp. 413–434, Oct. 2000. [Online]. Available: http://www.mitpressjournals.org/doi/10.1162/105474600566925

[27] M. Garau, D. Friedman, H. R. Widenfeld, A. Antley, A. Brogni, and M. Slater, "Temporal and spatial variations in presence: Qualitative analysis of interviews from an experiment on breaks in presence," *Presence*, vol. 17, no. 3, pp. 293–309, Jun. 2008.

[28] M. Meehan, B. Insko, M. Whitton, and F. P. Brooks, *Physiological Measures of Presence in Stressful Virtual Environments*. ACM Press, 2002, p. 645. [Online]. Available: http://portal.acm.org/citation.cfm?doid=566570.566630

[29] A. S. Rizzo and G. J. Kim, "A swot analysis of the field of virtual reality rehabilitation and therapy," *Presence, Teleoperators Virtual Environ.*, vol. 14, no. 2, pp. 119–146, 2005.

[30] M. Slater and A. Steed, "A virtual presence counter," *Presence: Teleoperators Virtual Environments*, vol. 9, no. 5, pp. 413–434, Oct. 2000, doi: 10.1162/105474600566925.

[31] V. Kelkkanen and M. Fiedler, "A test-bed for studies of temporal data delivery issues in a TPCAST wireless virtual reality set-up," in *Proc. 28th Int. Telecommun. Netw. Appl. Conf., (ITNAC)*, Nov. 2019, pp. 1–3. [Online]. Available: https://ieeexplore.ieee.org/document/8615297/

[32] *HTC Vive TPCast Add-On Makes VR Wireless*. Accessed: May 27, 2019. [Online]. Available: https://www.tpcastvr.com/single-post/2017/01/08/HTC-Vive-TPCast-Add-On-Makes-VR-Wireless

[33] J. Vasconcelos-Raposo, M. Bessa, M. Melo, L. Barbosa, R. Rodrigues, C. M. Teixeira, L. Cabral, and A. A. Sousa, "Adaptation and validation of the Igroup presence questionnaire (IPQ) in a Portuguese sample," *Presence, Teleoperators Virtual Environ.*, vol. 25, no. 3, pp. 191–203, Dec. 2016. [Online]. Available: http://www.mitpressjournals.org/doi/10.1162/PRES_a_00261

[34] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *Int. J. Aviation Psychol.*, vol. 3, no. 3, pp. 203–220, Jul. 1993. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1207/s15327108ijap0303_3

[35] M. H. Phan, J. R. Keebler, and B. S. Chaparro, "The development and validation of the game user experience satisfaction scale (GUESS)," *Hum. Factors*, vol. 58, no. 8, pp. 1217–1247, Dec. 2016. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0018720816669646

[36] T. Schubert, F. Friedmann, and H. Regenbrecht, "The experience of presence: Factor analytic insights," *Presence, Teleoperators Virtual Environ.*, vol. 10, no. 3, pp. 266–281, Jun. 2001. [Online]. Available: http://www.mitpressjournals.org/doi/10.1162/105474601300343603

GUILHERME GONÇALVES received the bachelor's degree from the University of Trás-os-Montes e Alto Douro (UTAD), Vila Real, Portugal, in 2015, where he is currently pursuing the M.Sc. degree in multimedia. His research interest is mainly multisensory virtual reality.

PEDRO MONTEIRO received the B.S. and M.S. degrees in computer science from the University of Trás-os-Montes e Alto Douro, Vila Real, Portugal, in 2015 and 2018, respectively.

Since 2016, he has been a Research Fellow with the INESC TEC, Porto, Portugal. His research interests include virtual reality, the use of multisensory stimuli in virtual reality applications, virtual reality interaction, and virtual reality user interfaces.

MIGUEL MELO is currently an Assistant Researcher with INESC TEC, specialized in computer graphics. He is also the Manager of the Multisensory Virtual Reality Laboratory. His research interests are computer graphics, HDR, and multisensory virtual reality. He is a member of the Executive Committee of Eurographics.

JOSÉ VASCONCELOS-RAPOSO is currently a Full Professor with the Department of Education and Psychology, UTAD, specialized in performance psychology. His research interests are in the use of technology in improving human performance applied in the most diverse fields of applications such as sports, health care, or training and certification. He is a member of INESC TEC-UTAD.

MAXIMINO BESSA received the Habilitation degree from the Department of Engineering, University of Trás-os-Montes and Alto Douro. He has been a Senior Researcher of INESC TEC, since 2009, and the Director of the Multisensory Virtual Reality Laboratory MASSIVE. He is currently an Assistant Professor with the Department of Engineering, University of Trás-os-Montes and Alto Douro. He has also been a member of the Eurographics Association, since 2003, and the Vice President of the Portuguese Computer Graphics Chapter for the period 2016–2018.