Journal of Computational Design and Engineering, 2020, 7(5), 577–590

doi: 10.1093/jcde/qwaa040
Journal homepage: www.jcde.org
Advance Access Publication Date: 9 April 2020

RESEARCH ARTICLE

I walk, therefore I am: a multidimensional study on the influence of the locomotion method upon presence in virtual reality

José L. Soler-Domínguez*, Carla de Juan, Manuel Contero and Mariano Alcañiz

Instituto de Investigación e Innovación en Bioingeniería (I3B), Universitat Politècnica de Valèncii, Camino de Vera, s/n, 46022 Valencia, Spain

*Corresponding author. E-mail: josodo@upv.es

Abstract

A defining virtual reality (VR) metric is the sense of presence, a complex, multidimensional psychophysical construct that represents how intense is the sensation of *actually being there*, inside the virtual environment (VE), forgetting how technology mediates the experience. Our paper explores how locomotion influences presence, studying two different ways of artificial movement along the VE: walking-in-place (through head bobbing detection) and indirect walking (through touchpad). To evaluate that influence, a narrative-neutral maze was created, from where 41 participants (N=41) had to escape. Measuring presence is a controversial topic since there is not a single, objective measure but a wide range of metrics depending on the different theoretical basis. For this reason, we have used for the first time, representative metrics from all three traditional dimensions of presence: subjective presence (SP) (self-reported through questionnaires), behavioral presence (BP) (obtained from unconscious reactions while inside the VE), and physiological presence (PP) [usually measured using heart rate or electrodermal activity (EDA)]. SP was measured with the ITC-SOPI questionnaire, BP by collecting the participants' reactions, and PP by using a bracelet that registered EDA. The results show two main findings: (i) There is no correlation between the different presence metrics. This opens the door to a simpler way of measuring presence in an objective, reliable way. (ii) There is no significant difference between the two locomotion techniques for any of the three metrics, which shows that the authenticity of VR does not rely on how you move within the VE.

Keywords: presence; interaction; locomotion; virtual reality

1. Introduction

The concept of presence is elusive and blurry. Imagine yourself in an immersive theatre play, like the iconic Sleep no More (https://www.punchdrunk.org.uk/sleep-no-more), where spectators move through the different stages and could interact with the actors and the props. Even when you know that everything within the stage is fiction, you empathize with the characters, your heart beats quickly in front of dramatic events, and, definitely, you act as if the situations were real. This suspension of disbelief, as was coined by the poet and philosopher Coleridge (1984), is indispensable when dealing with fictional works from different media: films, literature, theatre, or games. Feeling a synthetic environment and the events happening within as real, that is the sense of presence. Originally, when it was firstly defined at the 80's by MIT professor Marvin Minsky in the sci-fi

Received: 19 July 2019; **Revised:** 29 January 2020; **Accepted:** 9 February 2020

magazine Omnium Minsky (1980), the term made reference to telepresence, or the feeling of believing that you *actually* were in another remote place, even when from a cognitive point of view, you know that you are not. At these first stages of presence research, the focus was set on the technological aspects but as the topic has been developed, psychologist and even neuroscientists (Sanchez-Vives & Slater, 2005) have been attracted to this area.

Today, presence research is strongly linked to virtual reality (VR) since it is an immersive, evoking medium (Meehan, Razzaque, Insko, Whitton, & Brooks, 2005). VR causes that, both consciously and unconsciously, people act like there was no technology mediation, forgetting the head-mounted displays they are wearing, and that everything they seed is computer generated. In order to explain this phenomenon, researchers propose a wide range of theoretical frameworks that could be grouped in two big sets attending to the specific interpretation done over the presence concept. These groups do not integrate the whole research corpus but they include a great majority of the theories. This classification is based on the three biggest, generalist, presence surveys published along the last 20 years: Schuemie, van der Straaten, Krijn, and van der Mast (2001), Lee (2004), and Skarbez, Brooks, and Whitton (2017).

1.1. Presence as nonmediation

This theory was formally stated by Lombard and Ditton (1997) as the perceptual illusion of nonmediation. In his definition, perceptual indicates that the cognitive, sensory, and affective systems are permanently involved in an individual's environment. Additionally, the "illusion of nonmediation" happens when a person is not able to identify a medium within his/her environment and his/her reactions are similar to those that would take place if the medium was not present. Schuemie highlights this dualism (Schuemie et al., 2001): "part of the perception acknowledges that the experience is mediated by technology while another part does not." This theory is followed by Slater and Usoh (1993) and by the International Society for Presence Research (2000) as is surveyed by Skarbez et al. (2017).

1.2. Presence as being there

This is the most supported theoretical approach to presence, coined by Minsky (originally as *telepresence*), as said before and accepted by Steuer (1992), Schloerb (1995), Welch, Blackmon, Liu, Mellers, and Stark (1996), Mantovani and Riva (1999), Biocca, Harms, and Burgoon (2003), Riva, Davide, and IJsselsteijn (2003), Witmer, Jerome, and Singer (2005), and Mestre, Fuchs, Berthoz, and Vercher (2006) among others. It is based on the physical feeling of "being in the virtual environment" and from Steuer (1992) earlier works, presence has substituted the term telepresence in order to make it independent from technology or use domain (Lee, 2004). The presence of the virtual environment (VE) has a negative correlation with the presence of the real environment since both represent extremes of the same axis (Slater & Steed, 2000). Although this definition of presence is mainly subjectively reported (is only oneself who has the awareness of being in one place or another), Schloerb attempted to develop an objective metric for this presence conception: An individual is objectively present in one place if he/she is able to perform well in a proposed task (Schloerb, 1995). Schloerb's proposal gave a very simple measurement of presence, far from the complex alternatives implemented by that time, but it has no support by other researchers attending to its impartiality: An expert in a certain domain of skills will always perform better in a VE than another person who has not done that task before (Skarbez et al., 2017).

2. Quantifying Presence: Previous and Current Metrics

As other psychological states, presence can be quantified either using an in-out approach (subjective, introspective) or an out-out approach (objective, perceived). This last category could be split into two additional subcategories: behavioral, derived from embodied responses to virtual stimulus, and physiological, coming from the sympathetic neuronal activity.

Along the following subsections, we are going to provide a detailed background about previous work related to measuring presence in VEs.

2.1. Subjective measurement of presence

This set of methods includes every technique based on actively self-reporting to the researcher one or several aspects related to the experience in the VE. This method of measuring presence is usually supported by post-experiment questionnaires and it relies on the self-perception of how much "real" the VE is perceived by the user. The most relevant presence questionnaires (transmedia or VE focused) were summarized by Skarbez et al. (2017):

- Slater, Steed, and Usoh (1995a) (SUS questionnaire, 1995).
- Kim and Biocca (1997) (Arrival/Departure questionnaire, 1997).
- Baños et al. (2000) (Reality Judgment and Presence Questionnaire, RJPQ, 2000).
- Larsson, Västfjäll, and Kleiner (2001) (Swedish Viewer-User Presence Questionnaire, SVUP, 2001).
- Lessiter, Freeman, Keogh, and Davidoff (2001) (ITC Sense of Presence Inventory, ITC-SOPI, 2001).
- Vorderer et al. (2004) (MEC Spatial Presence Questionnaire, MEC-SPQ, 2001).
- Schubert, Friedmann, and Regenbrecht (2001) (Igroup Presence Questionnaire, IPQ, 2001).
- Bouchard et al. (2004) (Single-Item presence questionnaire, 2004).
- Witmer et al. (2005) (Presence Questionnaire, PQ, 2005).
- Takatalo, Nyman, and Laaksonen (2008) (Experimental Virtual Environment-Experience Questionnaire, EVEQ, 2008).
- Lombard et al. (2000); Lombard, Ditton, and Weinstein (2009) (Temple Presence Inventory, TPI, 2009).
- Chertoff, Goldiez, and LaViola (2010) (Virtual Experience Test, VET, 2010).

Attending to the work of Rosakranse and Oh (2014), the most relevant and used questionnaires are as follows:

(1) SUS Questionnaire (SUS).
(2) Witmer–Singer Presence Questionnaire (PQ).
(3) IGroup Presence Questionnaire (IPQ).
(4) ITC-Sense of Presence Inventory (ITC-SOPI).
(5) Lombard and Ditton Questionnaire.

All these questionnaires are intended to be answered once the virtual experience has ended [except from Bouchard et al. Single-Item questionnaire (Bouchard et al., 2004), which was designed to be asked also during the experience] and this makes them biased (based on fading memories about the previous experience), subjective (dependent on a personal reflection about a complex own feeling about reality, which affects its reliability), and act like a black box, hiding details about the changes on presence along the full experience (questionnaires give a discrete final value or a set of values).

On the other hand, questionnaires are easy to administer, affordable, and they also have a high ecological validity since there is no need to modify the VE in order to obtain values for this metric.

2.2. Behavioral measurement of presence

Intuitively, the more present feels a subject, the closer to reality will look their reactions. Reflex-like responses could act as indicators of presence in a VE (Mestre et al., 2006).

Held and Durlach (1991) firstly questioned if a teleoperator controlling a robot by distance and watching through his “eyes” would react to ducking or make any similar involuntary movement if a baseball bat was swung aiming to the telerobot eyes. Taking this idea, Sheridan (1992, 1996) proposed using people’s reactions as an objective measure of presence. Particularly, he proposed an experiment where individuals try to catch a ball or to avoid a thrown object inside the VE.

Behavioral measures have interesting improvements in front of questionnaires like:

- They are taken simultaneously to the virtual experience, avoiding bias of fading memories.
- They are nonintrusive since they are taken externally.
- They are (partially) objective although there is the need of a human person to register the reactions of the individuals and to code them as “natural” reactions.

However, on the other hand, they also lack ecological validity since in order to obtain natural reactions, researchers have to include additional elements into the VE like some dangerous or, at least, uncomfortable situations (heights, falling objects, strident sounds, etc.) that do not always fit with the topic of the VE.

2.3. Physiological measurement of presence

Different physiological measures like heart rate, skin temperature, or electrodermal activity (EDA), also known as skin conductance response or galvanic skin response, have been used as presence metrics. Even when most of them are related to arousal instead of presence and some of them could be altered by the physical activity done during the virtual experience (walking-in-place, swinging arms, etc.), some correlation has been established between them and the sense of presence.

Meehan, Insko, Whitton, and Brooks (2000) firstly and Wiederhold et al. (2001) after, succeeded in finding a correlation between self-reported questionnaires and physiological measures, specifically, EDA.

This metric is obviously objective *per se* but obtaining it is quite intrusive since external devices are needed and it could cause, to a certain extent, some loss of presence. Additionally, in the experiments mentioned before, the conditions that lead to increments in presence are both related to fear, making the VE not so ecological, and also, only applicable to a narrow subset of research scenarios.

3. Human–Computer Interaction in VR

Even when current VR systems are able to manage high-definition wireless head-mounted displays (HMD) and accurate wireless controllers, designers of VR experiences have to deal with an old challenge: How users are going to interact with the VE? Different approaches about designing interaction techniques and metaphors have been developed, being focused on performance, usability, realism, comfort, or a combination of them. Slater, Usoh, and Steed (1995b) established an interesting taxonomy, splitting interactions in a VE into two main categories: mundane and magical, attending to the level of fidelity between the virtual interaction and how that same action would be performed in the real world.

Despite the assumed temporary suspension of disbelief characteristic of mediated experiences that allows users to keep immersed while what they are watching, hearing, or touching is clearly unreal (Laurel, 2013), magical interactions have some identified flaws that have relevance in specific domains.

While mundane interactions are realized, to a certain extent, in the same way that they would be realized in the real world (moving from one point of the VE to another by walking in the real world, grabbing an object by touching it with a controller, and having pulled a trigger), magical interactions are metaphors created to overcome some limits or to soften some restrictions of VE. For example, grabbing objects without touching them (using a kind of telepathic force to move them from distance) or flying (traveling through the VE by touching a button or moving a joystick while standing still in the real world) represent adaptations or metaphors of certain actions pursuing effectiveness of interaction or ease of use.

Those metaphors, since represent alternative ways of taking an action, have some implications with our proprioceptive system. Sir Charles Scott Sherrington defined proprioception as “our secret sense, our sixth sense” (Sherrington, 1906) and, in a more detailed way, as the sensory flow that continuously and permanently gives to us the sensation that our body is “ours” and that we control it.

If there exist proprioceptive dissonances, like watching through our eyes that we are moving but not perceiving it with our muscles, tendons, or joints, it could cause a loss of presence and punctual diseases like cybersickness, a phenomenon that typically manifests itself as disorientation, eye strain, or nausea among others (Biocca, 1992). Additionally, in specific domains like training, those proprioceptive flaws could penalize transference of the trained actions in the virtual world to the real world (Slater, 2004).

In this experiment, we will focus on the study the implications of locomotion as the most common interaction in a 3D VE (Bowman, 2005).

3.1. Locomotion in VR

Immersive experience designers have to face a reiterative challenge: exceeding the physical limits of the room-scale tracking and give the users the possibility of moving through bigger environments. This design decision has several implications on performance, comfort, or presence and has to be informed by scientific evidence.

Bowman created a comprehensive taxonomy where different VR locomotion methods are classified attending to their complexity (Bowman, Koller, & Hodges, 1998):

- Travel: Control of the user’s viewpoint motion in the three-dimensional environment.
- Wayfinding: Cognitive process of determining a path based on visual cues, knowledge of the environment, and aids such as maps or compasses.

Figure 1: Most popular VR controllers: HTC Vive Controllers and Oculus Touch.

- Navigation: Together, travel and wayfinding make up the overall interaction called navigation.

Taking this classification, we put the focus on navigation skills, the one with higher cognitive implications.

3.2. Common methods of navigation

VR systems usually include a couple of wireless controllers (Fig. 1), one for each hand, with several photosensors or infrared LEDs (it depends on the platform), that allow them to be recognized by the tracking cameras. This tracking system detects and interprets a wide range movements and gestures from users, creating an almost infinite potential set of interactions that could be implemented.

Taking advantage of this relatively absolute freedom to design interactions, several navigation metaphors have been implemented. The most used and studied are Schuemie et al. (2001), Boletsis (2017), and Bozgeyikli, Raij, Katkoori, and Dubey (2019).

3.2.1. *Automatic locomotion*

This method could not be considered interactive at all. Although the user can still control the camera moving the head and is able to interact with the environment in other ways, the movement is out of his/her control. It is similar to a roller coaster or other fair attractions, where you move autonomously along the environment.

3.2.2. *Fix point teleport*

The fix point teleport metaphor is a restricted variation of the free teleport method. The user has a kind of pointer that allows her/him to select different destinations along the environment. Once selected (by pressing a button or pulling a trigger normally), her/his virtual avatar's position changes to the selected spot.

3.2.3. *Free teleport*

The free teleport metaphor allows the user to freely point to every (or almost every) place in the VE and to change instantly her/his position to the selected point. There are different approaches to manage the direction that the user faces when teleported: keeping the direction previous to the teleport, facing the old position when teleported, or selecting the new facing position before teleport.

3.2.4. *Indirect locomotion*

Indirect locomotion acts as a repository for a number of other metaphors, united by the common characteristic of moving the virtual avatar thanks to a disconnected interaction, that is, with an action that is not explicitly linked to movement. These metaphors come mainly from videogame culture: pushing a button, pulling a trigger or a joystick, touching a touchpad, etc. Usually, when performing such actions, the virtual avatars move in the direction that is facing the user but there are some alternatives, like moving in the direction the joystick points and keeping user's point of view. This family of methods feels inside the VE like flying or sliding.

3.2.5. *Walking-in-place*

This category also groups a number of other metaphors like head bobbing or arm swinging. Both examples of walking-in-place method are based on recognizing user's movements (by optical cameras or by tracking devices like HMD or controllers) and translate different gestures or actions (vertical displacements of head and alternate vertical displacement of hands) into movements of the virtual avatar. Some interesting accuracy recognition improvements have been developed using machine learning techniques.

3.2.6. *Stepper machine*

This is a different version of the walking-in-place metaphor, based on the use of a specific device, normally a stepper. Using this kind of devices improves dramatically the accuracy of movement recognition. The stepper devices go from the Wii®Balance Board to an adapted elliptic bike.

3.2.7. *Redirected walking*

This family of methods is mainly based on manipulating the VE in order to keep the user moving inside a small tracked space while he/she is convinced of being traveling along a greater environment. This illusion could be created by different means like using doors that act as portals or by slightly changing the orientation of the environment in a way that is imperceptible to the user and keeps him/her turning and turning permanently while in the VE the user is walking straight. There are other environment manipulations that have worked successfully in order to recreate redirected walking, usually based on architectural illusions or real-time adaptations.

3.2.8. *Real walking*

This metaphor is not a metaphor. Real means real and users' navigation in the real world is mapped under a 1:1 scheme to the VE. Usually, it needs: (i) strict level design, especially in VR systems with small room-scale tracking, which makes believable that users walk only in a 3 or 4×5 square meters space. It could be supported by storytelling, making the action of the VE happen in an office full of cubicles, in a submarine, or in a spaceship with small rooms; (ii) big physical spaces like stadiums or industrial warehouses and special tracking systems that could support huge scenarios.

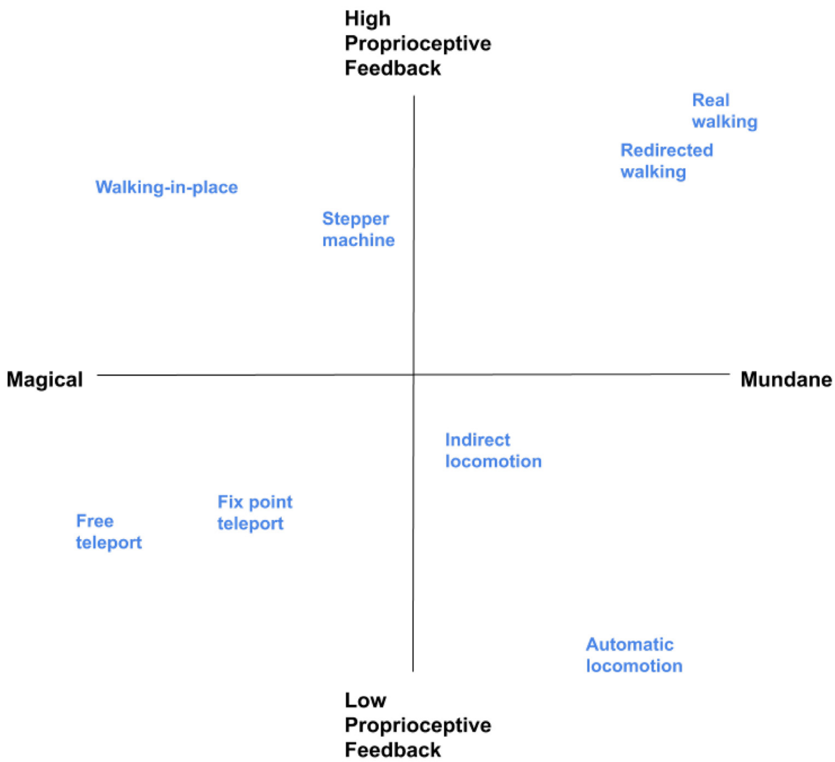

Figure 2: Bidimensional classification of locomotion methods.

In order to visually represent the different locomotion methods, we propose a bidimensional taxonomy (Fig. 2) based on the following:

- Level of proprioceptive feedback (PF): from low PF (LPF) to high PF (HPF). LPF could be associated with the inconsistency of sensory information received by the user of a VE and the actions carried out inside the VE.
- Level of *magic*: from mundane to magic, depending on how believable (from a real-world point of view) is the locomotion motion.

Attending to this classification, four subgroups are created: (Q1) magical-LPF; (Q2) magical-HPF; (Q3) Mundane-LPF; and (Q4) mundane-HPF.

On Q1, we have placed free teleport and fix point teleport since they represent an artificial way of moving and have very low PF, since the body is totally static when movement occurs.

Q2 puts together the walking-in-place and stepper machine locomotion techniques. Both have medium–high PF because they require user's physical movement to produce virtual movement. On the other side, since there is no real displacement, they have no full PF and they are considered quite magical since rotation and walking-in-place are strange for standard users.

On Q3, we have classified two artificial locomotion metaphores: indirect locomotion, which is considered mundane by its usual utilization on videogames, and automatic locomotion, popular by theme parks' amusement rides. Both of them have LPF.

Finally, on Q4 we included the natural locomotion methods, real walking, and redirected walking. Mostly mundane but having redirected walking with a lower PF since, even on the most efficient implementations, it has some sensorial singularities.

For this experiment, we have selected locomotion techniques from the, *a priori*, most opposed groups: mundane-LPF and magical-HPF in order to analyze this potential controversy.

4. Relationship Between Locomotion and Presence

As interaction plays a fundamental role in presence since it is a crucial factor in the acceptance and successful use of VR (Mütterlein & Hess, 2017) and locomotion represents a basic interaction on VR since it supports navigation inside a VE (Boletsis & Cedergren, 2019; Bozgeyikli, Raij, Katkoori, & Dubey, 2016; Hale & Stanney, 2014; Bowman, 2005), we are going to study the intersection of both of these concepts.

The intuitive idea behind this relationship is that choosing a locomotion technique for a VR environment that is closer to real human locomotion is going to increase both the subjective presence (SP; mainly reported through post-experiment questionnaires; Usoh, Catena, Arman, & Slater, 2000) and the behavioral presence (BP; physical reactions to the VE; Slater, McCarthy, & Maringelli, 1998).

This idea is rooted in the concept that users that navigate a VE using a locomotion technique that matches more accurately proprioceptive information from their own body and sensory feedback given by the computer will experiment a higher sense of presence. Research developed during the last 20 years (Usoh et al., 1999) has cultivated the idea that realistic locomotion techniques were associated with higher levels of presence. However, this statement is not always true *per se*; it has more complex implications. Along the next section, we are going to go deeper into previous research aiming to make clearer how presence is being measured and what kind of navigation metaphors

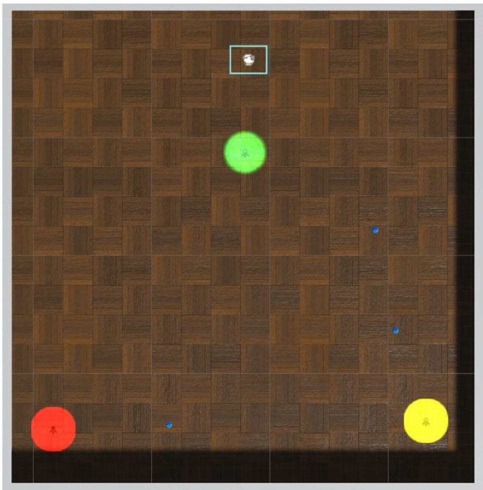

Figure 3: Training room (top view).

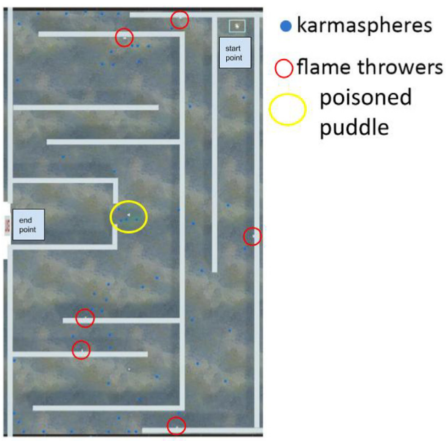

Figure 4: Maze (top view).

are being evaluated, and what will help us to establish a baseline.

4.1. Previous work

To a certain extent, the research developed to date on locomotion and presence is subsidiary to other topics (Youngblut, 2006) such as, for example, cybersickness, performance, usability, etc. We want to obtain relevant information about the influence of interaction, more specifically locomotion, on presence.

There have been several experiments oriented to measure locomotion method influence on presence but they usually focused on one metric, SP, and in one locomotion metaphor. Subjective presence is the most commonly used measure, based on subjective ratings through questionnaires (Schuemie et al., 2001). We want to go further in this direction, establishing a baseline between the three families of metrics (subjective, behavioral, and physiological) for presence and their relationship with the locomotion method.

This study is based on the previous work from Usoh et al. (1999), Zanbaka et al. (2004), Peck, Fuchs, and Whitton (2011), and Langbehn, Lubos, and Steinicke (2018). All the four studies are focused on locomotion and use only an SP measurement approach. In their results, there is no evidence of significant difference between sense of presence values for the different locomotion methods used.

It is a revealing fact that these four studies have a similar experimental design:

- Intersubject contrast: The participants (*n*) are divided in different groups, one per condition (locomotion metaphor). Each group only tries one navigation method and their measured values of presence are compared with the other groups.
- SUS questionnaire (Slater et al., 1995a): All four experiments used SUS as post-experience survey.

Only one study on locomotion and presence has combined two metrics. It was the Usoh et al. (1999) experiment. They created a score out from the following five components:

(1) A reported indicator of the extent to which the subject was aware of background sounds in the real laboratory (on a scale of 1 through 7);
(2) The extent to which their reaction when looking down over the pit was self-assessed as being similar to what it would have been in a similar situation in real life (on a scale of 1 through 7);
(3) The extent to which they had any vertigo or fear of falling when looking down over the virtual pit (on a scale of 1 to 7);
(4) Their willingness to walk out over the pit (on a 1 to 7 scale);
(5) The path they actually took to the chair on the other side of the pit; if they walked across the chasm the score was 0, and if they went around the edge the score was 1.

Attending to the research background, this is the first study on presence and locomotion metaphors that establish a relationship between the three families of metrics: subjective, behavioral, and physiological.

5. Methodology

An ad hoc scenario was developed in order to facilitate to the users an engaging virtual experience while testing the implications on presence of two different locomotion metaphors.

5.1. The VE

The environment was designed to combine of a task-oriented environment with an exploration goal. In this way, we covered the most common design options adopted on previous similar works. Additionally, we wanted to introduce some gamification elements like the karma-spheres, the shield, and the risks in order to create a game-like environment to promote engagement and intrinsical motivation for the experiment. As it is stated in McMahan (2013), engagement and presence are narrowly related.

Our VE is a decontextualized maze (Fig. 4) that participants must pass through from start to finish before the allocated time expires. The subjects have 3 minutes to escape from the maze (primary mission) and they are instructed to accumulate as much "karma" as possible (secondary mission). There are spheres distributed throughout the maze, which earn participants "karma" if they collect them. Furthermore, participants can lose "karma" if they are attacked by a risk.

These risks are also distributed throughout the maze and are of three types: fires, precipices, and slippery puddles. Some spheres are close to hazards and others are located in no-risk zones. Participants have the option of activating a shield, which protects them from the risks. When the shield is active, the user's speed is reduced and (s)he cannot collect any spheres. The shield is a finite resource that subjects need to optimize. While passing through the maze, the participants have information about the remaining battery life of the shield and how much of their allocated time remains.

Additionally, a training scenario (Fig. 3) was developed. It had all the mechanics implemented (picking up spheres, navigation, and shield) but it was a simple open, empty room. Inside, there were three lights: green, yellow, and red and three *karma-spheres*. In order to succeed on this training, users have to: (i) pick up all the spheres; (ii) activate the shield at least one time; and (iii) navigate through the lights in the order: green, yellow, and red. Once they had accomplished all the goals, the scene faded to black and the main environment was loaded.

5.2. Hardware and software details

For this experiment, we used HTC Vive VR HMD. This device offers an adequate performance (2160 × 1200 resolution, FOV-110 degrees, 90 Hz) for our VE and the tasks carried out by users. HTC Vive has all the capabilities expected in order to implement the locomotion techniques studied in this paper. All experiments were performed in an area of 3.5 m × 3.5 m. The VE was developed using the game engine Unity (version 2017.3.1f1) and it has a stable performance, fixed by code, of 60 FPS, running on a laptop HP OMEN 17-An104ns, with these characteristics: i7-8750H; 16GB; 1TB; 256SSD; 17.3 inch screen; GT 1050/W10.

5.3. The procedure

The participants responded to the self-report questionnaires on a personal computer. The process took approximately 40 minutes, and was completed in an experimental room, supervised by a research assistant. The subjects were thereafter conducted to a second experimental room where they received the following instructions:

> Welcome to the maze. You have 3 minutes to find the exit and, along the circuit, you should collect as many spheres as you can. Each sphere that you collect will earn you Karma. However, be careful! Exposing yourself to risks could make you lose Karma if they damage you. However, we won't leave you alone to face these dangers. You have a shield to protect you from these risks. This shield is a limited resource: it has a battery, which you should optimize. With the shield activated, the dangers can't harm you, but you will travel more slowly, and you will not be able to collect any spheres. Remember: you must exit the maze before your time runs out, and with the highest amount of Karma possible. Are you ready? Good luck!

After they had received the instructions, the participants underwent a practice session in which they familiarized themselves with the HMD device and the task interface. In this training scenario, the subjects learned how to navigate through the VE, how to collect spheres, and how to activate the shield. The training session took between 3 and 5 minutes. Once the goals of the training room were achieved, the main maze was loaded. This procedure was repeated twice, once per locomotion technique. In the training room and in the main maze, the same navigation metaphore was used. The maze structure and the distribution of karma-spheres and hazards were the same.

Paired samples t-test, α = 0.05, β = 0.8:

Effect	Small	Medium	Large
Effect size	0.2	0.5	0.8
Minimum total sample size	199	34	15

Figure 5: Sample size estimation by Cornish (2006).

5.4. Sample size determination

In order to determine an appropriate sample size aiming to achieve our objectives for this experiment, we used a two-factor decision pipeline:

- Factor (i) Previous Works: We selected the most relevant jobs on this topic from the previous bibliographic review aiming to figure out their average sample size. Our objective was to have a sample size larger than average sample size on related articles. Those papers, listed on section 4.1 Previous Work, were as follows: Usoh et al. (1999), Zanbaka et al. (2004), Peck et al. (2011), and Langbehn et al. (2018) and their sample size was, respectively, 33, 44, 36, and 33. The average sample size was 36.5, so, with our 41 individuals sample size, we accomplished our objective. This method, of using a similar sample size to other relevant studies on the topic, is explained in Kotrlik and Higgins (2001).
- Factor (ii) statistical power: With undetermined populations, the significance of results comes determined by the effect size. If we follow the relevant work of Cohen (1992) about statistical power, we could take into consideration that the sample size could be evaluated *a posteriori*, using the effect size. If statistical power of our findings does not reach the pre-fixed significance objectives, one method of increasing that power is increasing sample size. Power-based sample size calculations are related to hypothesis testing. Briefly, we can consider two types of errors: (i) Type I error (false positive): Concluding that there is an effect when there is not. $\alpha = P$(type I error) = level of statistical significance [$= P$ (reject H0 | H0 true)]; (ii) Type II error (false negative): Concluding that there is no effect when there actually is. $\beta = P$(type II error) [$= P$ (accept H0 | H1 true)]. The statistical power of a certain result set is defined to be 1 β [$= P$ (reject H0 | H1 true)]. This technique could also be used to estimate *a priori* a suitable sample size. Predefining acceptable values for α and β, we are able to find out the minimal sample size needed to achieve our statistical power requirements (Cornish, 2006). For an intrasubject experiment, with reasonable values for α (= 0.05) and β (=0.8) and expecting a conservative medium effect size, 34 individuals is the minimum sample size, as we can see in Fig. 5, so we are again over the objective.

5.5. The locomotion techniques

We decided to implement two different locomotion methods, following the VR locomotion typology from Boletsis (2017) (Fig. 6).

We have selected one locomotion method from each of the two main groups (Physical and Artificial) that have Continuous VR motion type and Open VR interaction space since these two characteristics permit more freedom for designers, being less restrictive over the environment:

- Indirect walking: This locomotion method belongs to the indirect walking set of metaphors. Its mechanic is inherited

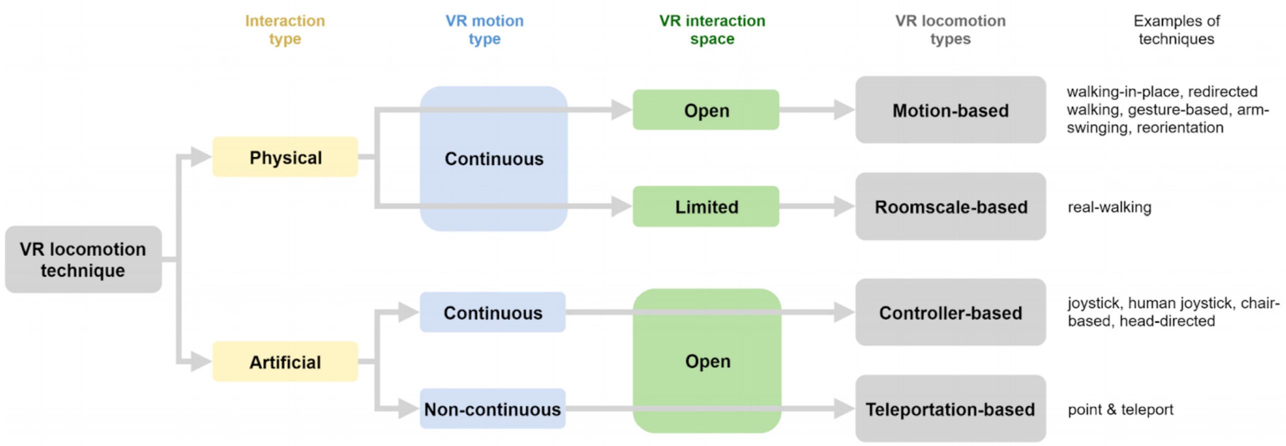

Figure 6: Locomotion types by Boletsis (2017).

from game tradition: pushing down on the controller's integrated touchpad moves the user's avatar in the direction (s)he is facing at 2 m/sec [speeds above 3 m/sec can increase cybersickness symptoms (So, Lo, & Ho, 2001)]. Indirect walking was included into the experiment because of its accuracy and soft learning curve.

- Walking-in-place (by head bobbing detection): Head bobbing is part of the walking-in-place set of methods and it is based on the recognition of vertical movements of the head when users are pretending to walk but without any displacement. It is the HMD that is responsible for detecting those movements through its sensors. This method was chosen for its PF and easiness of implementation for reduced tracking places.

Both locomotion techniques were implemented in C# on Unity3D. They were based on the SteamVR 2.0 and VR Locomotion Essentials – v2.5 commercial libraries and were rigorously tested in order to validate their implementation. Prior to the experiment, both of them were evaluated on their accuracy and optimization by a focus group. This focus group was formed by five people with different levels of VR and 3D game experience.

5.6. The metrics

As far as we are concerned, this is the first experiment combining the three predominant approaches oriented to presence measuring: SP, BP, and physiological presence (PP).

5.6.1. *Subjective presence*

In order to evaluate the subjective perspective of presence, we have selected the ITC-Sense of Presence Inventory, a cross-media presence questionnaire developed by Lessiter, Freeman, Keogh, and Davidoff in 2001 (Lessiter et al., 2001). This questionnaire is built of 44 items (in the revised version; originally it had 63 items). A five-point Likert scale (1 strongly disagree; 5 strongly agree) was chosen as the response option for all items. Internally, it is segmented into four different factors: (i) sense of physical space; (ii) engagement; (iii) ecological validity; and (iv) negative effects (NEs).

5.6.2. *BP*

By BP, we mean the extent to which individuals' behaviors, reactions, or perceptions when immersed into the virtual experience are similar to those that would happen in the real world. This metric was constructed from the data collected by researchers about users' reactions to sensory stimulus (visual hazards, sounds, etc.) while walking along the maze. The codification of this reaction has no relationship with the Slater's (Slater & Steed, 2000) BIP (Breaks in Presence) theory, based on the idea that events (sounds mainly) in the real world could be omitted by users if they are fully immersed (high sense of presence) into the virtual world. We tried to maintain a "neutral real world" in order to maximize the immersive experience. As in Usoh et al. (1999), a score was constructed from a reported indicator of the extent to which the subject experienced "real" reactions to different hazardous situations. For each hazard, the following reactions were registered:

- Fire throwers (ducking and/or jumping backwards and/or shouting).
- Dangerous pool (jumping ahead and/or going slowly).
- Abyss (going slowly).

Each reaction registered from the previous list counted as 1 point in our score, being the count of all of them, the final Behavioral Presence Score.

5.6.3. *PP*

EDA was chosen as the metric for PP. EDA represents electrical changes, measured at the surface of the skin, that arise when the skin receives innervating signals from the brain. There is a great agreement among researchers about the theory that EDA is produced by the sympathetic nervous system, thus allowing EDA to provide a sensitive measure of sympathetic nervous system arousal (Critchley, 2002; Picard, Fedor, & Ayzenberg, 2015).

In order to obtain values of EDA from each user, an Empatica E4 wristband (Fig. 7) was used (https://www.empatica.com/en-eu/research/e4/). This gadget is a wearable research device that offers real-time data about EDA, with a great ecological validity.

The wrist measurement of EDA offers more compatibility with holding the VR controllers and additionally it has shown greater responsivity than measurement on the traditional palmar surface (Sano, Picard, & Stickgold, 2014). The Empatica E4 provides a way to capture electrical conductance (inverse of resistance) across the skin. It achieves this by passing a minuscule amount of current between two electrodes in contact with the skin. The units of measurement for conductance are microSiemens (μ S). As Empatica checks and stores electrical conductance several times per second, after a light post-processing

Figure 7: Empatica E4 wristband.

Table 1: Means and standard deviations (SD) from ITC-SOPI questionnaire.

	Locomotion metaphor			
	Indirect walking		Walking-in-place	
	Mean	SD	Mean	SD
Physical space	3.3288	0.6936	3.3002	0.6255
Engagement	3.7134	0.6613	3.6273	0.6339
Ecological validity	2.9220	0.9010	2.7902	0.7589
Negative effects	2.0446	0.7612	2.5366	0.9367

(cleaning and normalizing), we used the average measurement along the whole experience.

6. Results

6.1. Subjective presence

Means and standard deviation for the ICT-SOPI questionnaire can be found in Table 1.

Analysis of variance was conducted on the presence measures attending to locomotion metaphor. Firstly, we checked the normality of the distribution using the Lilliefors test, which is used to test the null hypothesis that data come from a normally distributed population (Lilliefors, 1967). For each dependent variable (Physical space, Engagement, Ecological validity, and Negative effect values), it returned 0, which means that the null hypothesis was accepted, except for NEs results for indirect walking condition.

The effect size was calculated using Cohen's d (Sullivan & Feinn, 2012) and results were low (<0.2) for each variable except from NEs, a consistent result with the ANOVA test:

- Physical Space: d=.04.
- Engagement: d=.13.
- Ecological validity: d=.15.
- Negative effects: d=.57.

A one-way between subjects ANOVA was conducted to compare the effect of navigation metaphors on four factors of ITC-SOPI questionnaire. There was no significant effect of the locomotion method on the SP at the p<.05 level on any of the first three factors (PS, E, and EV) but we found a relevant difference on the fourth (NE):

- Physical space: $F(1, 80)$=0.04, p=.84.
- Engagement: $F(1, 80)$=0.36, p=.54.
- Ecological validity: $F(1, 80)$=0.51, p=.47.
- Negative effects: $F(1, 80)$=6.81, p=.01.

Attending to the nonnormal distribution of the data from the NEs factor for the walking-in-place independent variable, we performed an additional nonparametric test, Kruskal–Wallis (Breslow, 1970), and obtained p<.05 (p=.013), which confirmed the significant difference between conditions for this specific factor.

6.2. BP

The results on Fig. 8 show the total count of behavioral reactions inside the VE during the virtual experience:

Numerical results were as follows:

- IndirectWalking (M=0.84, SD=1.26); Total count = 38;
- HeadBobbing (M=0.2, SD=0.50); Total count = 9.

The Lilliefors test showed the nonnormality of the data and Kruskal–Wallis revealed a p<.05 (d=.0076). This significant difference in the effect of locomotion type on this BP metric is obvious since indirect walking condition registered almost four times more reactions than walking-in-place. The Cohen's d obtained was d=.67, which represents a medium effect size (d>.5 and d<.8).

6.3. PP

Prior to the experiment, a baseline of EDA was registered for each participant. Baseline is generally considered to be the average tonic level of an individual during rest conditions and in the absence of any discrete environmental event/external stimulus. With this baseline, it is possible to calculate the differential between the average of EDA values obtained during the experiment and the baseline, as it was explained in subsection 5.6.3:

$$\triangle EDA = \text{mean}(EDA_{\text{maze}}) - \text{mean}(EDA_{\text{baseline}}).$$

Through this calculus, we obtained means and SD for each condition, summarized in Fig. 9.

Applying again the Lilliefors normality test, we obtained that EDA values follow a nonnormal distribution. Due to this, Kruskal–Wallis was applied again and it thrown p=.028(< .05), so there is a significant difference between both locomotion methods.

Finally, the effect size obtained using Cohen's d was d=.85, which represents a large effect size (d>.8).

6.4. Correlation matrix

Figure 10 reflects correlation coefficients using Kendall's tau (Kendall, 1948) for each pair of dependent variables. The coefficients highlighted in red indicate which pairs of variables have correlations significantly different from zero.

We found an interesting negative correlation between BP for the HeadBobbing condition and the NE factor from the ITC-SOPI questionnaire for the same condition. Here, Kendall's $\tau = -.29$ shows an intuitive relationship between presence and comfort. If individuals are uncomfortable inside the VE, they are not able to be fully immersed into the virtual experience and this could affect their level of presence.

Additionally, even when all three dimensions (subjective, behavioral, and physiological) have shown no correlation between them, they internally have significant correlations, which

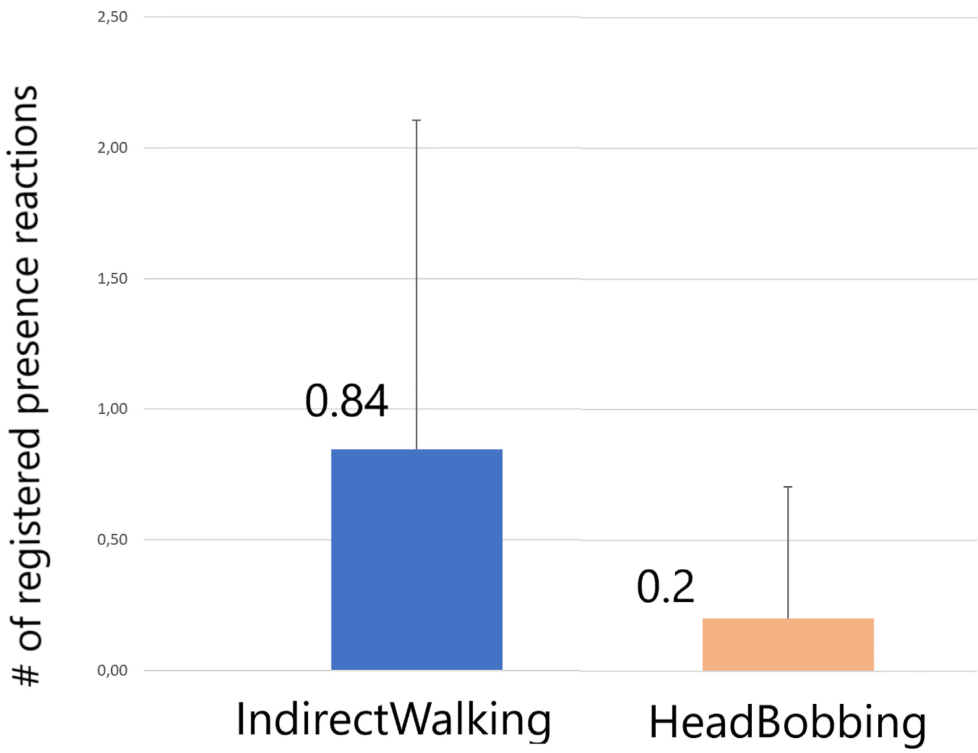

Figure 8: BP summary.

ensures certain robustness of those metrics that are taken individually into consideration.

7. Discussion

This experiment aimed to gain additional knowledge about the influence, of interaction in general and locomotion metaphors particularly, on the sense of presence inside a VE. With this objective in mind, two locomotion methods have been tested (indirect walking and walking-in-place by head bobbing detection) and three different measures for presence were used.

Slater, Usoh, & Steed (1994) used the term "body-centered interaction" for techniques that try to match proprioception and sensory data. We tried here a walking-in-place technique (based on head bobbing detection) that is a clear example of this. The other method (indirect walking) fails on that matching.

Attending to previous work on comfort and cybersickness, the indirect walking metaphor should have obtained higher scores on the NE factor of the ITC-SOPI questionnaire but, surprisingly, it was the other method, the walking-in-place, that obtained worst values in this area.

This could be understood thinking about how similar is the touchpad control in VR to the regular games' controls. As our population was very young and they are usually used to playing games, this locomotion metaphor, even with low proprioceptive conditions, was easier to be understood and assimilated.

Making reference about the three dimensions of metrics for presence, although no correlation has shown between them, some interesting findings could be highlighted.

Firstly, it is evident that the complex and blurry concept of presence has several ways to be measured, each of them with a different approach, trying to capture a small slice of the subjective experience of a user inside a virtual environment.

We tried to shed some light on a holistic approach, combining the three methods, and findings are clear: Each metric, subjective, behavioral, and physiological, is not measuring the same. To a certain extent, it could be said that each of them is measuring *a different presence*. As several previous studies, post-experiment questionnaires are not good at discriminating different levels of presence among various locomotion methods. This could be rooted on the biased remembering of the experience that users have.

BP seems a robust metric since it reflects real-world reactions, but it is to be said that those reactions are usually triggered by nonecological events: hazardous situations, strong noises, etc. That has a dual effect: (i) design of VE has always to contain certain elements in order to check presence in real time and this would have great limitations with certain topics or domains; (ii) it strongly relies on user psychological profile and 3D environments expertise: the more used they are to navigate hostile environments like in videogames, lesser their reactions will be to events inside the VE, as we could check with the participants of this study. Finally, PP could represent the most objective metric but even when today's gadgets are nonintrusive and this promotes higher levels of ecology in the experiments, EDA has shown weakness discriminating mood arousal from high levels of physical activity (like running, jumping, etc.; Meehan et al., 2000).

In an earlier work (Slater et al., 1994), Slater et al. used the term "body-centered interaction" for techniques that try to match proprioception and sensory data. The walking-in-place method is a clear example of this. For this reason, as the base of knowledge we have on this topic would suggest, it should generate higher levels of presence than a nonrealistic locomotion method, like indirect walking. We have found that this is not supported by evidence in our experiment. In both, subjective and behavioral, it obtained inferior values than the indirect

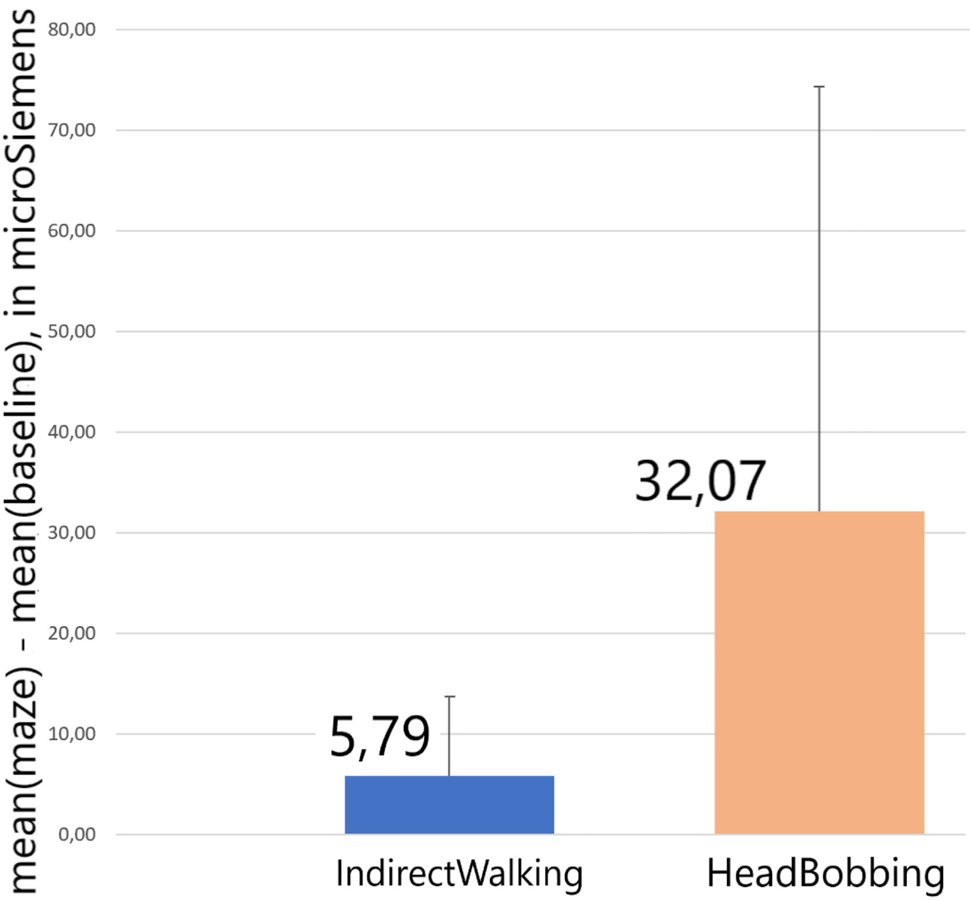

Figure 9: PP summary.

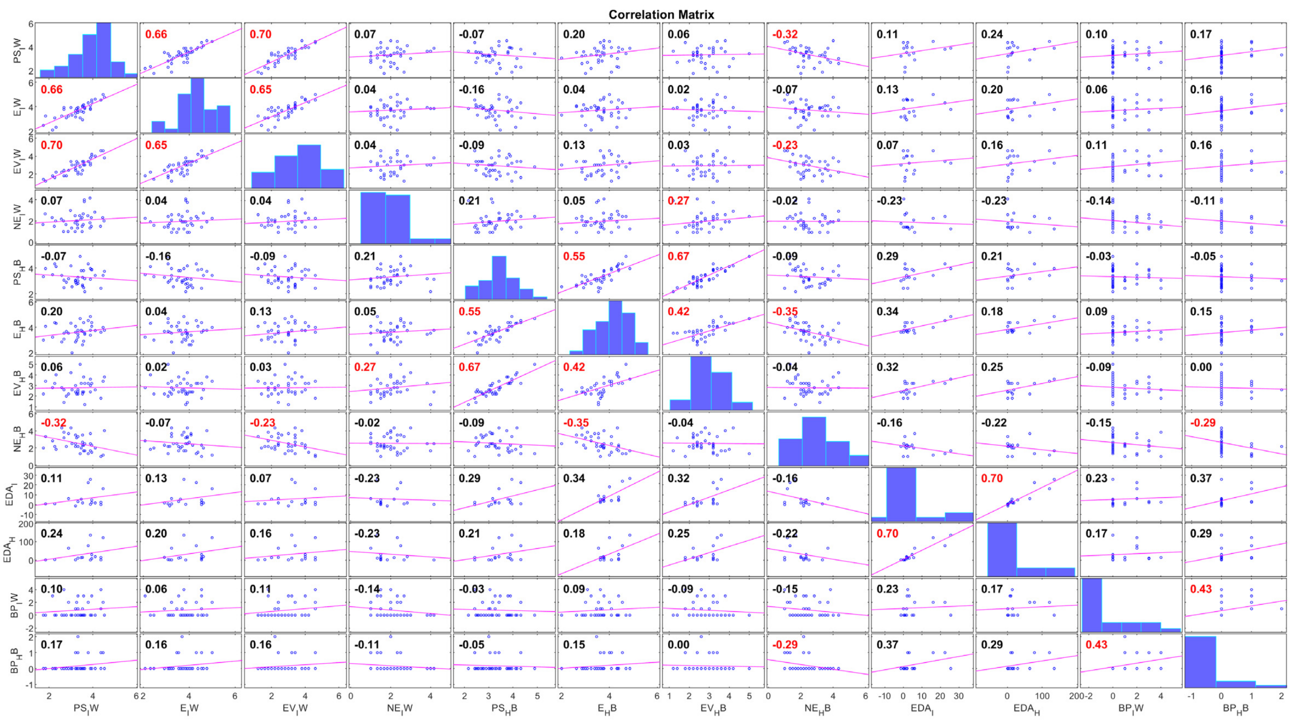

Figure 10: Correlation matrix.

walking metaphor. In the third metric, the PP based on EDA, it obtained higher values but surely linked with the level of physical activity. That links with the perceptual/psychological immersion presence theory (Palmer, 1995; Biocca & Delaney, 1995) that is rooted on the idea that presence is, mainly, a sensory experience and high levels of physical activities could distract senses from perception.

Attending to prior studies and our results, we are able to add the following two main ideas to the topic:

- Referred to the methodology and metrics used on presence–locomotion evaluation, our results push us to question how presence has been evaluated until now. To a certain extent, presence has been revealed on our experiment, more likely to be higher when users are more comfortable with the interaction design, independently from the kind of presence measured (subjective, behavioral, or physiological). This fact is supported by our findings, where a lesser natural locomotion method, like indirect walking (by button pressing), obtains a higher sense of presence under the behavioral approach. PP has an intense positive correlation with physical activity, so it is not a reliable source to measure presence with locomotion methods that require intense physical activity.
- Referred to the design of VR experiences, as we said on the previous point, locomotion methods with high levels of physical activity could both distract perception and make the experience uncomfortable, penalizing presence. This concept gives us the idea that a customized locomotion method (at least eligible), linked to the personal traits of the user like physical condition, experience with games, etc., could improve dramatically user experience on VR experiences. In such an emotional medium, the customization of interaction (or real-time adaptation) could be the key to a better and wider penetration of the technology.

So, in our humble opinion, the focus on the presence and locomotion research should stand on how to adapt the interaction method to the user, attending to their real-time presence metrics, more than trying to figure out which locomotion method is "the best." This idea is supported by recent theories, summarized in the study from Riva, Wiederhold, and Mantovani (2019), where the concept of predictive coding (PC) is developed. PC theory suggests that the "brain actively maintains an internal model (simulation) of the body and the space around it, which provides predictions about the expected sensory input and tries to minimize the amount of prediction errors (or 'surprise')" (Riva et al., 2019, p. 88). This increasingly popular theory also states that VR tries to mimic the brain model as much as possible: The more the VR model is similar to the brain model, the more the individual feels present in the VR world. In this way, it could be said that any locomotion technique with actual leg movement (real walking, walking-in-place, etc.) should generate higher presence sensations. Despite this hypothesis, the results from our study say that presence is not so much affected by this fact, so new variables have to be introduced. As far as we have analyzed, 3D gaming experience could alter brain models to the extent that pushing a controller button could be associated to a consistent movement, generating a similar presence than the natural movement. Further study is needed on this premise.

8. Conclusion

This study has faced two different VR locomotion metaphors: one of them from the subgroup magical-HPF (walking-in-place) and the other representing the mundane-LPF (indirect walking) set of techniques. Our original research questions: Do locomotion methods influence sense of presence? To what extent? How we can measure that? have clearer answers than before this experiment. Using an intrasubject comparison and an SP approach, locomotion method has no influence on presence. When individuals get used to the VR experience, they feel present in a similar way using different locomotion methods or, at least, they are not able to internally perceive different levels of presence. The behavioral metrics correlate positively with the mundane (common in videogames)-LPF technique of indirect walking. This represents that, although this locomotion metaphore is far from being a natural interaction, it makes people comfortable and being less focused on the interaction itself, increasing presence.

9. Limitations and Future Work

The major limitation of this study is the strongest correlation between physical activity and EDA. To a certain extent, every locomotion method linked to an interaction with high physical activity could have altered their presence metrics related to arousal.

Future studies should repeat the experimental conditions of this research but trying another physiological metric that has greater independence from physical activity, like eye tracking. Some behavioral metrics have also to be added in order to explore how body movements (head, hands, etc.) are able to represent a reliable metric for presence.

Additionally, a wider set of locomotion methods could be tested in order to find out if new correlations could be established between them and different presence metrics.

Finally, the gaming and 3D background of participants and a basic psychological profiling could set a baseline that will support a better understanding about how presence is originated and how brain model is altered from a standard configuration to a "3D mode," where atypical interactions start to being considered natural.

Conflict of interest statement

Declarations of interest: none.

References

Baños, R. M., Botella, C., Garcia-Palacios, A., Villa, H., Perpiñá, C., & Alcaniz, M. (2000). Presence and reality judgment in virtual environments: A unitary construct? *CyberPsychology & Behavior*, *3*(3), 327–335.

Biocca, F. (1992). Will simulation sickness slow down the diffusion of virtual environment technology? *Presence: Teleoperators & Virtual Environments*, *1*(3), 334–343.

Biocca, F., & Delaney, B. (1995). Immersive virtual reality technology. *Communication in the Age of Virtual Reality*, 15, 32.

Biocca, F., Harms, C., & Burgoon, J. K. (2003). Toward a more robust theory and measure of social presence: Review and suggested criteria. *Presence: Teleoperators & Virtual Environments*, *12*(5), 456–480.

Boletsis, C. (2017). The new era of virtual reality locomotion: A systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction*, *1*(4), 24.

Boletsis, C., & Cedergren, J. E. (2019). Vr locomotion in the new era of virtual reality: An empirical comparison of prevalent techniques. *Advances in Human-Computer Interaction*, *2019*(4), 1–15.

Bouchard, S., Robillard, G., St-Jacques, J., Dumoulin, S., Patry, M.-J., & Renaud, P. (2004). Reliability and validity of a single-item measure of presence in vr. In *Proceedings of the 2nd International Conference on Creating, Connecting and Collaborating through Computing* (pp. 59–61). IEEE.

Bowman, D. A. (2005). *3D user interfaces: Theory and practice*. Boston, MA, USA: Addison-Wesley.

Bowman, D. A., Koller, D., & Hodges, L. F. (1998). A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual Reality*, *3*(2), 120–131.

Bozgeyikli, E., Raij, A., Katkoori, S., & Dubey, R. (2016). Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play* (pp. 205–216). New York, NY, USA: ACM.

Bozgeyikli, E., Raij, A., Katkoori, S., & Dubey, R. (2019). Locomotion in virtual reality for room scale tracked areas. *International Journal of Human-Computer Studies*, *122*, 38–49.

Breslow, N. (1970). A generalized Kruskal-Wallis test for comparing k samples subject to unequal patterns of censorship. *Biometrika*, *57*(3), 579–594.

Chertoff, D. B., Goldiez, B., & LaViola, J. J. (2010). Virtual experience test: A virtual environment evaluation questionnaire. In *Proceedings of the 2010 IEEE Virtual Reality Conference (VR)* (pp. 103–110). IEEE.

Cohen, J. (1992). Statistical power analysis. *Current Directions in Psychological Science*, *1*(3), 98–101.

Coleridge, S. T. (1984). *Biographia literaria, or, biographical sketches of my literary life and opinions* (**Vol.** *7*). Princeton, NJ, USA: Princeton University Press.

Cornish, R., (2006). Statistics: An introduction to sample size calculations. University of Loughborough Mathematics Learning Support Center, Retrieved on September 2019 from https://www.lboro.ac.uk/media/wwwlboroacuk/content/mlsc/downloads/Samplesize.pdf, pp. 3.

Critchley, H. D. (2002). Electrodermal responses: what happens in the brain. *The Neuroscientist*, *8*(2), 132–142.

Hale, K. S., & Stanney, K. M. (2014). *Handbook of virtual environments: Design, implementation, and applications*. Boca Raton, FL, USA: CRC Press.

Held, R., & Durlach, N. (1991). Telepresence, time delay and adaptation. *Pictorial Communication in Virtual and Real Environments* (pp. 232–246). Philadelphia, PA, USA: Taylor & Francis, Inc.

(2000). Presence defined, International Society for Presence Research. Last retrieval from https://ispr.info on 2019-04-02.

Kendall, M. G. (1948). *Rank correlation methods*. C. Griffin.

Kim, T., & Biocca, F. (1997). Telepresence via television: Two dimensions of telepresence may have different connections to memory and persuasion. *Journal of Computer-Mediated Communication*, *3*(2), JCMC325.

Kotrlik, J., & Higgins, C. (2001). Organizational research: Determining appropriate sample size in survey research appropriate sample size in survey research. *Information Technology, Learning, and Performance Journal*, *19*(1), 43.

Langbehn, E., Lubos, P., & Steinicke, F. (2018). Evaluation of locomotion techniques for room-scale VR: Joystick, teleportation, and redirected walking. In *Proceedings of the Virtual Reality International Conference (VRIC)*(pp. 1–9).

Larsson, P., Västfjäll, D., & Kleiner, M. (2001). The actor-observer effect in virtual reality presentations. *CyberPsychology & Behavior*, 4(2), 239–246.

Laurel, B. (2013). *Computers as theatre*. Boston, MA, USA: Addison-Wesley.

Lee, K. M. (2004). Presence, explicated. *Communication Theory*, *14*(1), 27–50.

Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A cross-media presence questionnaire: The itc-sense of presence inventory. *Presence: Teleoperators & Virtual Environments*, *10*(3), 282–297.

Lilliefors, H. W. (1967). On the Kolmogorov–Smirnov test for normality with mean and variance unknown. *Journal of the American Statistical Association*, *62*(318), 399–402.

Lombard, M., & Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication*, *3*(2), JCMC321.

Lombard, M., Ditton, T. B., Crane, D., Davis, B., Gil-Egui, G., Horvath, K., Rossman, J., & Park, S. (2000). Measuring presence: A literature-based approach to the development of a standardized paper-and-pencil instrument. I n *Proceedings of the Third International Workshop on Presence, Delft, the Netherlands* (*Vol. 240*, pp. 2–4).

Lombard, M., Ditton, T. B., & Weinstein, L. (2009). Measuring presence: The temple presence inventory. In *Proceedings of the 12th Annual International Workshop on Presence* (pp. 1–15).

Mantovani, G., & Riva, G. (1999). "Real" presence: How different ontologies generate different criteria for presence, telepresence, and virtual presence. *Presence*, *8*(5), 540–550.

McMahan, A. (2013). Immersion, engagement, and presence: A method for analyzing 3-d video games. *The video game theory reader* (pp. 89–108). Abingdon, UK: Routledge.

Meehan, M., Insko, B., Whitton, M., & Brooks, F. (2000). An objective surrogate for presence: Physiological response. In *Proceedings of the 3rd International Workshop on Presence* (*Vol. 2*).

Meehan, M., Razzaque, S., Insko, B., Whitton, M., & Brooks, F. P. (2005). Review of four studies on the use of physiological reaction as a measure of presence in stressfulvirtual environments. *Applied Psychophysiology and Biofeedback*, *30*(3), 239–258.

Mestre, D., Fuchs, P., Berthoz, A., & Vercher, J. (2006). Immersion et présence. *Le Traité de la RéAlité Virtuelle* (pp. 309–338). Paris, France: Ecole des Mines de Paris.

Minsky, M. (1980). Telepresence. *Omni Magazine*, *2*(9), 44–52.

Mütterlein, J., & Hess, T. (2017). Immersion, presence, interactivity: Towards a joint understanding of factors influencing virtual reality acceptance and use. In *AMCIS2017 Proceedings: Adoption and Diffusion of Information Technology (SIGADIT)*. Boston, USA.

Palmer, M. T. (1995). Interpersonal communication and virtual reality: Mediating interpersonal relationships. In B. Frank, & R. L. Mark (eds.), *Communication in the age of virtual reality* (pp. 277–299). Broadway Hillsdale, NJ, USA: L. Erlbaum Associates Inc.

Peck, T. C., Fuchs, H., & Whitton, M. C. (2011). An evaluation of navigational ability comparing redirected free exploration with distractors to walking-in-place and joystick locomotion interfaces. In *Proceedings of the Virtual Reality Conference (VR), 2011 IEEE* (pp. 55–62). IEEE.

Picard, R. W., Fedor, S., & Ayzenberg, Y. (2015). Multiple arousal theory and daily-life electrodermal activity asymmetry. *Emotion Review*, *8*(1), 1–14.

Riva, G., Davide, F., & IJsselsteijn, W. (2003). Being there: The experience of presence in mediated environments. *Being there: Concepts, effects and measurements of user presence in synthetic environments* (**Vol.** 5). Amsterdam, the Netherlands: IOS Press.

Riva, G., Wiederhold, B. K., & Mantovani, F. (2019). Neuroscience of virtual reality: From virtual exposure to embodied medicine. *Cyberpsychology, Behavior, and Social Networking*, *22*(1), 82–96.

Rosakranse, C., & Oh, S. Y. (2014). Measuring presence: the use trends of five canonical presence questionnaires from 1998-2012. In *Challenging Presence: Proceedings of the 15th International Conference on Presence* (pp. 25–30).

Sanchez-Vives, M. V., & Slater, M. (2005). From presence to consciousness through virtual reality. *Nature Reviews Neuroscience*, 6(4), 332.

Sano, A., Picard, R. W., & Stickgold, R. (2014). Quantitative analysis of wrist electrodermal activity during sleep. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology*, 94(3), 382–389.

Schloerb, D. W. (1995). A quantitative measure of telepresence. *Presence: Teleoperators & Virtual Environments*, 4(1), 64–80.

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments*, 10(3), 266–281.

Schuemie, M. J., van der Straaten, P., Krijn, M., & van der Mast, C. A. (2001). Research on Presence in Virtual Reality: A Survey. *CyberPsychology & Behavior*, 4(2), 183–201.

Sheridan, T. B. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators & Virtual Environments*, 1(1), 120–126.

Sheridan, T. B. (1996). Further musings on the psychophysics of presence. *Presence: Teleoperators & Virtual Environments*, 5(2), 241–246.

Sherrington, C. S. (1906). *The integrative action of the nervous system*. New York, NY, USA: Charles Scribner's Sons.

Skarbez, R., Brooks, F. P. Jr, & Whitton, M. C. (2017). A survey of presence and related concepts. *ACM Computing Survey*, 50(6), 96:1–96:39.

Slater, M. (2004). How colorful was your day? Why questionnaires cannot assess presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, 13(4), 484–493.

Slater, M., & Steed, A. (2000). A virtual presence counter. *Presence: Teleoperators & Virtual Environments*, 9(5), 413–434.

Slater, M., & Usoh, M. (1993). Representations systems, perceptual position, and presence in immersive virtual environments. *Presence: Teleoperators & Virtual Environments*, 2(3), 221–233.

Slater, M., Usoh, M., & Steed, A. (1994). Steps and ladders in virtual reality. In *VRST '94: Proceedings of the Conference on Virtual Reality Software and Technology*(pp. 45–54). Singapore: World Scientific.

Slater, M., Steed, A., & Usoh, M. (1995a). The virtual treadmill: A naturalistic metaphor for navigation in immersive virtual environments. *Virtual environments' 95* (pp. 135–148). Vienna: Springer.

Slater, M., Usoh, M., & Steed, A. (1995b). Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 2(3), 201–219.

Slater, M., McCarthy, J., & Maringelli, F. (1998). The influence of body movement on subjective presence in virtual environments. *Human Factors*, 40(3), 469–477.

So, R. H., Lo, W., & Ho, A. T. (2001). Effects of navigation speed on motion sickness caused by an immersive virtual environment. *Human Factors*, 43(3), 452–461.

Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of Communication*, 42(4), 73–93.

Sullivan, G. M., & Feinn, R. (2012). Using effect size–or why the p value is not enough. *Journal of Graduate Medical Education*, 4(3), 279–282.

Takatalo, J., Nyman, G., & Laaksonen, L. (2008). Components of human experience in virtual environments. *Computers in Human Behavior*, 24(1), 1–15.

Usoh, M., Arthur, K., Whitton, M. C., Bastos, R., Steed, A., Slater, M., & Brooks, F. P. Jr (1999). Walking> walking-in-place> flying, in virtual environments. In *Proceedings of the 26th Annual Conference on Computer graphics and Interactive Techniques* (pp. 359–364). ACM Press/Addison-Wesley Publishing Co, NY, United States.

Usoh, M., Catena, E., Arman, S., & Slater, M. (2000). Using presence questionnaires in reality. *Presence: Teleoperators & Virtual Environments*, 9(5), 497–503.

Vorderer, P., Wirth, W., Gouveia, F. R., Biocca, F., Saari, T., Jäncke, F., Böcking, S., Schramm, H., Gysbers, A., Hartmann, T., Klimmt, C., Laarni, J., Ravaja, N., Sacau, A., Baumgartner, T., & Jäncke, P. (2004). Mec spatial presence questionnaire (mecspq): Short documentation and instructions for application. *Report to the European Community, Project Presence: MEC (IST-2001-37661)*, *3*, 5–3.

Welch, R. B., Blackmon, T. T., Liu, A., Mellers, B. A., & Stark, L. W. (1996). The effects of pictorial realism, delay of visual feedback, and observer interactivity on the subjective sense of presence. *Presence: Teleoperators & Virtual Environments*, 5(3), 263–273.

Wiederhold, B. K., Jang, D. P., Kaneda, M., Cabral, I., Lurie, Y., May, T., Kim, I., Wiederhold, M. D., & Kim, S. (2001). An investigation into physiological responses in virtual environments: An objective measurement of presence. *Towards cyberpsychology: Mind, cognitions and society in the internet age*(Vol. 2). Amsterdam: IOS Press.

Witmer, B. G., Jerome, C. J., & Singer, M. J. (2005). The factor structure of the presence questionnaire. *Presence: Teleoperators & Virtual Environments*, 14(3), 298–312.

Youngblut, C. (2006). What a decade of experiments reveals about factors that influence the sense of presence. Tech. Rep., Alexandria, VA, USA: Institute for Defense Analyses.

Zanbaka, C., Babu, S., Xiao, D., Ulinski, A., Hodges, L., & Lok, B. (2004). Effects of travel technique on cognition in virtual environments. In *Proceedings of the IEEE Virtual Reality 2004* (pp. 49–286). IEEE.