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Research Article

VR Locomotion in the New Era of Virtual Reality: An Empirical Comparison of Prevalent Techniques

Costas Boletsis [1] and Jarl Erik Cedergren [2]

[1] *SINTEF Digital, Forskningsveien 1, Oslo, Norway*
[2] *University of Oslo, Gaustadalléen 23B, Oslo, Norway*

Correspondence should be addressed to Costas Boletsis; konstantinos.boletsis@sintef.no

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The latest technical and interaction advancements within the virtual reality (VR) field have marked a new era, not only for VR, but also for VR locomotion. In this era, well-established, prevalent VR locomotion techniques are mostly used as points of comparison for benchmarking of new VR locomotion designs. At the same time, there is the need for more exploratory, comparative studies of contemporary VR locomotion techniques, so that their distinguished interaction aspects can be documented and guide the design process of new techniques. This article presents a comparative, empirical evaluation study of contemporary and prevalent VR locomotion techniques, examining the user experience (UX) they offer. First, the prevalent VR locomotion techniques are identified based on literature, i.e., walking-in-place, controller/joystick, and teleportation. Twenty-six adults are enrolled in the study and perform a game-like task using the techniques. The study follows a mixed methods approach, utilising the System Usability Scale survey, the Game Experience Questionnaire, and a semistructured interview to assess user experiences. Results indicate that the walking-in-place technique offers the highest immersion but also presents high levels of psychophysical discomfort. Controller/joystick VR locomotion is perceived as easy-to-use due to the users' familiarity with controllers, whereas teleportation is considered to be effective due to its fast navigation, although its visual 'jumps' do break the users' sense of immersion. Based on the interviews, the users focused on the following interaction dimensions to describe their VR locomotion experiences: (i) immersion and flow, (ii) ease-of-use and mastering, (iii) competence and sense of effectiveness, and (iv) psychophysical discomfort. The study implications for VR locomotion are discussed, along with the study limitations and the future direction for research.

1. Introduction

Virtual reality (VR) locomotion is an essential interaction component enabling navigation in VR environments [1, 2]. Since the early days of VR, various locomotion techniques have been developed and studied, targeting seamless and user-friendly navigation in virtual environments [1, 3] while key theoretical models and classifications were developed to ground the constructive contributions of VR locomotion techniques [3–6].

Over the last few years, a major hardware-driven revival has had significant effects on how the users experience and use VR [5, 7, 8]. The introduction of the Oculus Rift development kit 1 in 2013 is considered a significant milestone for VR, indicating when the VR revival took place and VR became accessible, up-to-date, and relevant again [5, 7, 9–11]. From a human-computer interaction (HCI) perspective, the technological revival of VR has produced new and updated interaction metaphors, designs, and tools, thus affecting the users' experiences and the research of the field [5, 9]. This VR revival marked what has been characterised as the 'new era of virtual reality' [5, 12–14].

The technical and interaction advancements in the new era of VR have also marked a new era for VR locomotion [5]. As a result, new locomotion techniques have been developed, and past ones have been significantly updated [5]. For instance, point-and-click teleportation is now a widely used VR locomotion technique and is fully integrated in commercial VR systems, such as the HTC Vive and the Oculus Rift [1]. Motion-based locomotion techniques—including swimming, climbing, flying and walking-in-place—have become more robust and user-friendly [5, 15, 16], while the real-walking locomotion technique, which was a cumbersome construction [17], now comes with commercial headsets [5, 18, 19].

However, the latest advancements for head mounted displays (HMD) and VR tracking systems have strongly affected the HCI research around VR locomotion by facilitating more constructive work [5, 9, 20]. A considerable amount of literature focuses on the technical and performance aspects of new or updated VR locomotion techniques, while the study of the VR locomotion users' experiences is overshadowed [5, 21]. At the same time, more exploratory, comparative studies of contemporary VR locomotion techniques are needed so that their distinguished interaction aspects can be documented and guide the design process of new techniques [5].

This article presents a comparative, empirical evaluation study of contemporary, prevalent VR locomotion techniques. The goal of this work is to examine the user experience (UX) of these VR locomotion techniques, as well as related factors, such as usability and technical performance. Ultimately, this work builds on authors' previous work in the field [5, 9, 22] and it aspires to contribute by documenting the interaction aspects of the most prevalent VR locomotion techniques and by producing knowledge that can be further used by researchers and developers to formulate conceptual works, e.g., design guidelines and frameworks, and to guide the design of new or updated VR locomotion techniques [9, 23].

The article is organised as follows. Section 2 presents the related work. Section 3 identifies the contemporary, prevalent VR locomotion techniques that will be compared and empirically evaluated. Section 4 describes the comparative, empirical study, presenting the utilised methodology and its results, and Section 5 discusses the study's results and its overall research implications. Section 6 concludes the paper.

2. Background

The VR revival and the recently introduced devices offered a level of technical homogeneity for VR locomotion techniques, thus providing a common ground and allowing for the comparison and analysis of these techniques. Previous work by Boletsis [5] was based on that premise in order to conduct a systematic literature review of empirical studies on VR locomotion techniques from 2014 to 2017. The review documented several interaction aspects of the reviewed studies and proposed a typology of VR locomotion techniques; research gaps in the field were also discovered and discussed. The current work builds on the acquired knowledge from that review and addresses the research gaps presented therein.

As documented in the aforementioned systematic literature review, there are several comparative studies of VR locomotion techniques from 2014 onwards. Many of these studies introduce newly constructed VR locomotion techniques—such as Wii-Leaning [24], Virtusphere [25], Myo Arm-Swinging [26], Point & Teleport [1], Accelerometer Walking-in-Place (A-WIP) [16], LMTravel [27], VR-STEP [28], Node-based locomotion [29]—and benchmark their performance aspects through empirical comparisons against other popular techniques, such as controller/joystick locomotion, walk-in-place, teleportation, real walking, redirected walking, and gaze-directed locomotion. Other comparative studies follow the same benchmarking approach for newly constructed techniques but under a specific theme. In [30], Bozgeyikli et al. address the needs of VR users with autism disorder by comparatively evaluating three VR locomotion techniques: Flying, Flapping, and Trackball. The works of Kitson et al. [20] and Hashemian and Riecke [31] focus on comparing leaning-based motion cueing interfaces for VR locomotion, introducing and evaluating chair-based techniques, such as MuvMan and NaviChair. Sarupuri et al. [32] evaluate and compare game-controller-based VR locomotion techniques, focusing on their newly constructed Trigger-Walking technique. Ferracani et al. [15] examine gesture-enabled VR locomotion; they present and evaluate two new techniques called Tap and Push. The work of Langbehn et al. [33] explores omnidirectional walk-in-place user interfaces by comparing the newly constructed Leaning-Amplified-Speed Walking-in-Place (LAS-WIP) against the traditional walk-in-place interface.

Current empirical, comparative studies around VR locomotion techniques focus on presenting newly constructed VR locomotion techniques while using the comparison against popular or well-established VR locomotion techniques as a way to justify and evaluate implemented design decisions. However, the HCI field of VR locomotion would also benefit from using the interaction aspects of prevalent VR locomotion techniques not only as *a point of comparison* for benchmarking purposes, but also as *a point of inspiration* for informing new designs of VR locomotion techniques, at the early stages of the design process. Empirical, comparative studies of exploratory nature about contemporary, widely used, and well-established VR locomotion techniques can address this issue. Naturally, some steps have been taken in the right direction—such as the work of Langbehn et al. [21] evaluating the effect of room-scale VR locomotion techniques on the users' cognitive map building abilities—but more studies are needed to cover the VR locomotion techniques' wide range of experiential and interaction qualities.

3. Prevalent VR Locomotion Techniques

As a first step towards the empirical comparison of the VR locomotion techniques and to ensure the scientific rigour of the process, the choice of the examined techniques should be scientifically justified, an action that is oftentimes sidelined or even ignored in the field's comparative studies. Herein, the prevalent VR locomotion techniques in the new era of Virtual Reality are identified on a scientific basis and then are studied and compared. In this context, the prevalent VR locomotion techniques are considered to be the most frequently implemented and studied techniques in peer-reviewed, scientific literature. For their identification, the four distinct VR locomotion types, formed in the systematic literature review of Boletsis [5], are utilised:

(i) *Motion-based*: the VR locomotion techniques that fall under this type, utilise some kind of physical

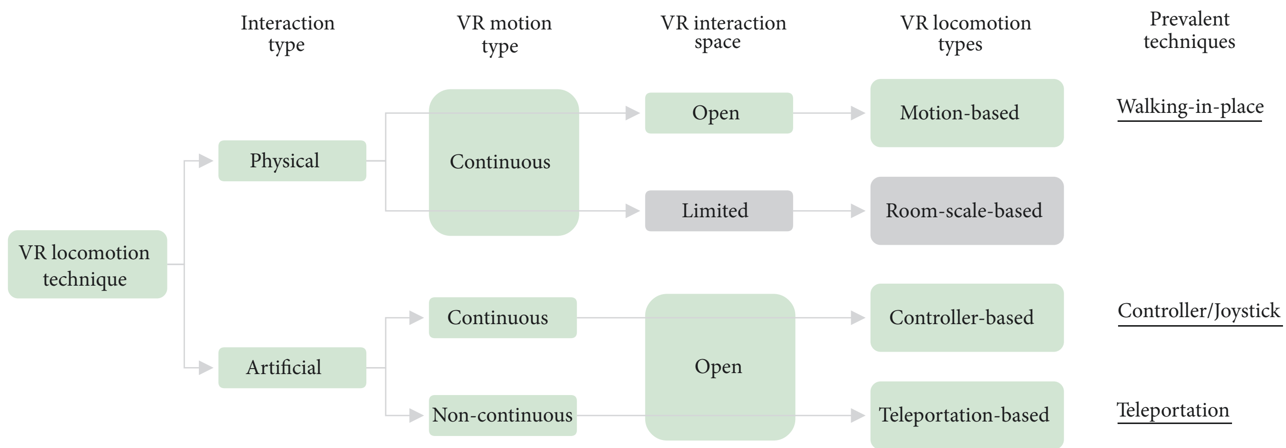

Figure 1: The typology of VR locomotion techniques [5]. The VR locomotion types and interaction aspects represented in the empirical comparison (in *green* boxes), leading up to the three identified, prevalent techniques.

movement to enable interaction while supporting continuous motion in open VR spaces [5].

(ii) *Room-scale-based*: this VR locomotion type utilises physical movement to enable interaction, and it supports continuous motion, as with the motion-based type; however, the interaction takes place in VR environments whose size is limited by the real environment's size [5, 21].

(iii) *Controller-based*: this VR locomotion type utilises controllers to artificially move the user in the VR environment. The VR interaction space is open, and the motion is continuous [5].

(iv) *Teleportation-based*: the VR locomotion techniques that fall under this type utilise artificial interactions in open VR spaces with noncontinuous movement. The user's virtual viewpoint is instantaneously teleported to a predefined position by utilising visual 'jumps' [5].

The identification of the well-established, prevalent VR locomotion techniques is based on these VR locomotion types, since they originate from a reliable literature review of peer-reviewed scientific articles and they represent a range of VR locomotion techniques with different interaction aspects. Moreover, the types' analysed interaction aspects establish a baseline for a fair comparison. More specifically, three out of the four VR locomotion types support open VR interaction spaces (Figure 1), i.e., their techniques enable navigation in virtual environments that surpass the limits of the real environment. However, room-scale-based VR locomotion provides limited interaction space capabilities due to the limitations that the physical environment places on the size of the virtual one. Since virtual environments that go beyond the physical limits of the real world are the norm [1], and in order to create a uniform baseline for comparison, the *motion-based*, *controller-based*, and *teleportation-based* VR locomotion types are ultimately included in this study (Figure 1, green boxes).

Therefore, based on the literature review's [5] documented instances of studied VR locomotion techniques for the three included types, the prevalent VR locomotion techniques identified and compared in this study are the following:

(i) *Walking-in-place*: the user performs virtual locomotion by walking-in-place, i.e., using step-like movements while remaining stationary [5, 33].

(ii) *Controller/joystick*: the user uses a controller to direct the movement in the virtual environment [5, 25].

(iii) *Teleportation*: the user points to where he/she wants to be in the virtual world, and the virtual viewpoint is instantaneously teleported to that position. The visual 'jumps' of teleportation result in virtual motion being noncontinuous [1, 5, 30].

Figure 1 visualises the identification process based on the typology of [5], demonstrating the included (in green boxes) and excluded (in grey boxes) VR interaction aspects and VR locomotion types, as well as the resulting prevalent VR locomotion techniques.

4. Study Methodology

The goal of this study is to investigate which experiential factors, empirical qualities and system features are most relevant for VR locomotion by evaluating three prevalent techniques and receiving feedback that can be of use for future related designs. To this end, an empirical, comparative study with a mixed methods approach is carried out in order to assess the three VR locomotion techniques. A strong focus on experiential and introspective data is given, as the study aims for a richer understanding of the specific factors affecting user experience for VR locomotion techniques, an aspect that many of the more quantitative studies sometimes neglect [20].

The study gathers data from usability and user experience questionnaires in order to form an overview of the techniques' experiential performance; it also collects data from semistructured interviews in order to gain a 'thick description' of the users' experiences. This is a validated

Figure 2: A user testing the walking-in-place (WIP) technique. Video demonstration of virtual navigation: http://boletsis.net/vrloco/wip/.

Figure 3: Interacting with the HTC Vive controller for the controller/joystick technique (*left*) and a view of the virtual environment (*right*). Video demonstration of virtual navigation: http://boletsis.net/vrloco/cont/.

methodology that looks not only at human behaviour but also at its context, thus giving results external validity [20, 34, 35]. Finally, the study applies a within-subjects' design with three experimental conditions, based on the three compared VR locomotion techniques.

4.1. Materials

4.1.1. VR Locomotion Techniques. The examined VR locomotion techniques were developed using the HTC Vive headset (https://www.vive.com) and the SteamVR SDK for Unreal Engine 4 by Epic Games. The HTC Vive headset is well established in the VR consumer market, and it is designed to utilise room-scale technology for turning a room into a 3D space via sensors. It enables high-fidelity graphics with a display resolution of 1080×1200 (2160×1200 combined pixels), 90Hz refresh rate, a 110° field-of-view, and a full 360° room-scale body tracking with the included lighthouse infrared sensors; the interaction takes place through the included HTC Vive controllers. In addition, the system supports the HTC Vive tracker, an additional sensor which can be used for tracking physical objects and translating them into actions or objects in the virtual environment.

VR locomotion speed for walking-in-place and controller/joystick were set close to typical human locomotion speeds (1,4-3m/s), as suggested in the related literature [29, 33, 36, 37], since fast movement speeds have been shown to hasten the onset of motion-sickness.

(i) *Walking-in-place*: for the walking-in-place (WIP) technique, the user's limb movements should be translated into VR motion while the user is moving in place [5, 21, 28, 30, 38]. In this study, the HTC Vive tracker (mounted on the users' right foot) in combination with the HTC Vive controllers was utilised to register and control the VR locomotion speed and direction, respectively (Figure 2). The VR locomotion speed depended on the users' real locomotion speed, i.e., the faster the users were moving in place, the faster their avatar was moving in the virtual environment. Maximum speed was set at 3 m/s, i.e., jogging pace. The average speed was identified as approximately 2 m/s based on informal, pilot observations, which was further supported by the literature [33]. A 'wizard-of-Oz' approach was followed for simulating the registration of the left footstep's velocity by duplicating the velocity of the right footstep, i.e., the right footstep's velocity is translated into the velocity of two virtual 'steps', in the context of continuous movement. The direction of movement was determined by the direction of the HTC Vive controllers and was visualised as a pointing arrow in the HMD interface. Therefore, to change the direction of movement, the users had to physically turn their bodies into the desired direction. Arm-swinging—that is, the natural swinging motion of the arms, and, in this case, of the controllers, when walking or jogging—was used to initiate the avatar's movement. The lack of arm-swinging would stop the movement, thus overcoming the limitation of having only one foot tracker and significantly minimising movement's starting and stopping latency.

(ii) *Controller/joystick*: the kind of controller can range from a simple joystick to a game controller, a keyboard or a trackball [5, 25, 30, 38, 39]. In this study, the HTC Vive controllers were utilised for enabling controller-based VR locomotion. The controllers featured a touchpad. Pressing the touchpad (of any of the two controllers) activated movement, while the position of the thumb on the touchpad regulated the speed of movement (Figure 3). Maximum speed was set to be equal to the average WIP speed, as suggested in the VR literature [25, 33], i.e., approximately 2 m/s. The direction of movement was determined by the direction of the HTC Vive controllers and was visualised as a pointing arrow in the HMD interface.

(iii) *Teleportation*: for the VR teleportation technique, the pointing for teleporting can take place by using a controller or making a pointing gesture [1, 5, 30, 40]. In this study, the HTC Vive controllers and, more specifically, the grip button of the controllers were

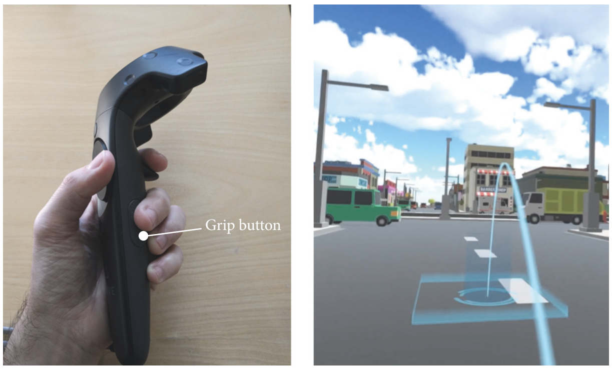

Figure 4: Interacting with the HTC Vive controller for the teleportation technique (*left*) and a view of the virtual environment (*right*). Video demonstration of virtual navigation: http://boletsis.net/vrloco/teleport/.

utilised. When the button was pushed, a ray followed by a marker on the ground of the virtual environment appeared as a visual cue, which indicated the location of movement (Figure 4). Instant movement was executed by releasing the button. That visual 'jump' was estimated to cover a short distance in the vicinity of the avatar, as demonstrated in Figure 4. The users' body direction determined the direction of teleportation.

4.1.2. Questionnaires and Interview. Demographic data were collected at the initial stage of the study, and they included age, gender, frequency of VR use ('never', 'rarely', 'frequently', and 'everyday'), and experience with VR technology (participants listing devices they have used).

The comparative study utilised the *Game Experience Questionnaire* [41], the *System Usability Scale* questionnaire [42], and a *semistructured interview*. Each of the questionnaires has a long history of use in the human factors community and in VR evaluation studies.

The Game Experience Questionnaire (GEQ) is a user experience questionnaire that has been used in several domains (such as gaming, augmented reality, and location-based services) because of its ability to cover a wide range of experiential factors with good reliability [43–47]. The use of GEQ is also established in the VR domain in several studies around such topics as navigation and locomotion in virtual environments [48, 49], haptic interaction in VR [50], VR learning [51], cyberpsychology [52], and VR gaming [53]. In this study, the dimensions of Competence, Sensory and Imaginative Immersion, Flow, Tension, Challenge, Negative Affect, Positive Affect, and Tiredness (from the In-Game and Post-Game versions of the GEQ) were considered to be relevant and useful for the evaluation of the techniques. The GEQ questionnaire asked the user to indicate how he/she felt during the session based on a series of statements. It contained 16 statements (e.g., 'I forgot everything around me'), rated on a five-point intensity scale ranging from 0 ('not at all') to 4 ('extremely').

The System Usability Scale (SUS) [42] is an instrument that allows usability practitioners and researchers to measure the subjective usability of products and services. In the VR domain, SUS has been utilised in several studies around such topics as VR rehabilitation and health services [54–58], VR learning [59], and VR training [60]. SUS is a ten-item questionnaire that can be administered quickly and easily, and it returns scores ranging from 0 to 100. SUS scores can be also translated into adjective ratings, such as 'worst imaginable', 'poor', 'OK', 'good', 'excellent', 'best imaginable' and into grade scales ranging from A to F [61]. SUS has been demonstrated to be a reliable and valid instrument, robust with a small number of participants, and to have the distinct advantage of being technology agnostic, meaning that it can be used to evaluate a wide range of hardware and software systems [42, 62–64].

The semistructured interviews collected the participants' comments. They were asked about what they liked and did not like about the evaluated VR locomotion techniques and why. The interviewer was able to follow up on the participants' comments until each topic was covered.

4.2. Participants. The participants were recruited between December 2017 and May 2018 in the Oslo area. They had to be physically able to use VR technology, however previous experience with VR was not a prerequisite. They were made aware of the potential risk of motion-sickness and the fact that they could opt out of the study at any time. All the participants gave informed consent to participate in the study.

4.3. Environment. The virtual environment used in the study is a city called 'Simple Town', by Synty Studios (https://www.unrealengine.com/marketplace/simple-town). The city contains multiple assets and interesting locations for the user to navigate while utilising the implemented locomotion techniques. Its graphical style is simplistic and cartoon inspired. The choice of a cartoonesque virtual environment was made so that the user can get a game-like feeling from it so as to become more easily engaged and, ultimately, focused on the task at hand [65].

In order to motivate the users for navigating the virtual environment, a checkpoint gaming approach was utilised. With each VR locomotion technique, the users had to perform a task; the task involved locating four specific places in the virtual environment (called checkpoints) in a sequence, e.g., first locate the auto repair shop and then locate the cinema, etc. (Figure 5). Each task had its own specific checkpoints which were placed in strategic places so that participants had to navigate the whole environment. The goal of the task was to locate the checkpoints within a 15-minute timeframe. The task was completed either when the user had located all four checkpoints successfully or when he/she had spent 15 minutes in the virtual environment (i.e., unsuccessful task completion), whichever condition was met first. The targeted task duration was between 7 to 15 minutes, and several pilot testings took place for evaluating the task duration based on the placement of the checkpoints. A total of three different tasks were designed for serving all three VR locomotion techniques. The task of locating checkpoints or

Figure 5: The checkpoints' order for the three tasks (visualised in three different colours: red, green, and blue).

point of interests and the targeted task duration have been common goals and practices in several empirical studies on VR locomotion [1, 20, 21, 66–68]. Such tasks address and 'fight' the experimenter's effect, since the users can focus on a specific goal while using the VR locomotion techniques in use context, thus forming a more representative impression of the techniques. The targeted task duration gives users the appropriate time to experience the techniques.

4.4. Procedure. First, the participants were presented with an introduction to the study and gave their informed consent. They then filled out their demographic and VR experience questionnaires (approximately 10 minutes). Then, the first task and its four checkpoints were presented by the experimenters while the participants were also given some trial time to navigate freely and experience a 'clean' version of the VR environment, i.e., without checkpoints, and the VR locomotion technique (approximately 5-7 minutes). Afterwards, the task was carried out by the participants (7-15 minutes). While navigating, the participants could give verbal feedback, and the experimenters were keeping notes so that they could address these topics in the interview. When the task was completed, the SUS and GEQ questionnaires were completed (approximately 5 minutes). A 5-minute break followed. Then, the second task followed the same process with another VR locomotion technique. After the third task with the final VR locomotion technique, the semistructured interview took place (approximately 15 minutes). The testing order of the VR locomotion techniques and their assigned tasks were randomised. The total time to complete the study was estimated between 106 and 136 minutes. The procedure is depicted in Figure 6.

4.5. Statistical Analysis. All data were analysed using the Statistical Package for Social Sciences (SPSS) version 25. Significance level was set at $p < 0.05$. Descriptive analysis was used to depict the demographic data of the participants and to analyse the GEQ and SUS values. The nonparametric Friedman test was used to detect differences between the techniques' performance based on the GEQ and SUS values. For post hoc analysis and pair-wise comparisons, the Wilcoxon signed rank test was applied. The interview data were transcribed and then analysed with NVivo through open and axial coding, where core concepts, themes, and ideas were identified. Two researchers coded the data independently, and the interrater reliability was assessed.

4.6. Results. Twenty-six participants ($N = 26$, mean age: 25.96, SD: 5.04, male/female: 16/10) evaluated the three VR locomotion techniques. Six participants had never experienced VR before; ten participants had experienced VR rarely, and ten participants had experienced VR frequently. From the twenty participants that had previously experienced VR, four of them had used HMD devices (e.g., Oculus Rift, HTC Vive, and Playstation VR) and mobile VR headsets (e.g., Samsung Gear VR, Google Cardboard); fourteen had used only HMD devices, and two participants had used only mobile VR headsets. All participants successfully completed the sessions.

A total of 78 tasks (26 participants X 3 tasks/participant) took place. The mean task-completion time was 590.32 seconds (SD: 192.65, range: 326-900). Nine tasks out of 78 were 'unsuccessfully' completed, i.e., the 15-minute deadline expired before the four checkpoints were located.

4.6.1. GEQ. Figure 7 displays the mean values from the GEQ questionnaire (with standard deviation bars) and Table 1 presents the post hoc analysis of the GEQ scores using the Wilcoxon signed rank test. An individual analysis of each GEQ component follows, comparing the three VR locomotion techniques based on the Friedman test and the Wilcoxon signed rank test.

(i) *Competence.* The Friedman test showed statistically significant differences in the Competence score between the different techniques: $X^2(2) = 16.455$, $p < 0.001$. Post hoc analysis with the Wilcoxon signed rank tests revealed significant differences when comparing the Competence score of WIP and Teleportation ($Z = -3.033$, $p = 0.002$) in favour of Teleportation with a mean rank score of 11.88, as well as between WIP and Controller ($Z = -2.478$, $p = 0.013$) in favour of Controller (mean rank score of 13.17).

(ii) *Sensory and Imaginative Immersion.* The Friedman test results showed statistically significant differences in the Sensory and Imaginative Immersion component between the three techniques, $X^2(2) = 6.099$, $p = 0.047$. The post hoc analysis indicated statistically significant differences in the pair-wise comparison between WIP and Teleportation ($Z = -2.304$, $p = 0.021$), in favour of WIP.

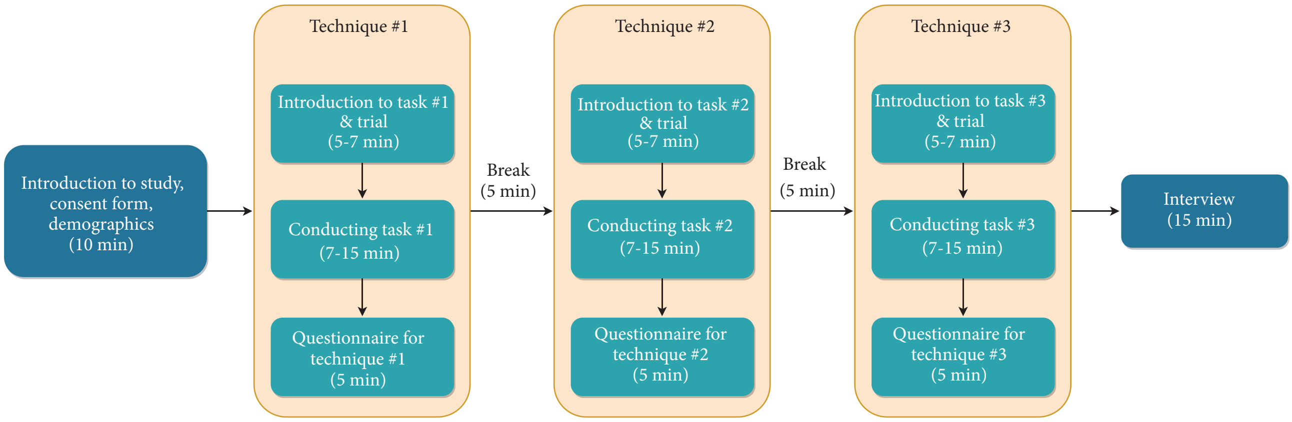

FIGURE 6: The procedure of the study.

TABLE 1: Summary of the pair-wise comparisons from the Wilcoxon signed rank tests.

GEQ Components	Pair of Techniques (Mean Rank)	Z	Sig. (2-tailed)
Competence	WIP (10.53) – Controller (13.83)	-2.607	0.009
	WIP (8.13) – Teleportation (12.82)	-3.240	0.001
	Controller (9.17) – Teleportation (10.38)	-1.660	0.097
Sensory and Imaginative Immersion	WIP (9.90) – Controller (8.63)	-1.333	0.182
	WIP (11.03) – Teleportation (8.90)	-2.304	0.021
	Controller (10.67) – Teleportation (10.25)	-0.877	0.380
Flow	WIP (8.83) – Controller (5.72)	-1.003	0.316
	WIP (9.63) – Teleportation (8.13)	-1.534	0.125
	Controller (9.35) – Teleportation (7.08)	-1.335	0.182
Tension	WIP (9.63) – Controller (8.81)	-1.835	0.066
	WIP (11.90) – Teleportation (7.89)	-0.992	0.321
	Controller (8.33) – Teleportation (9.36)	-1.325	0.185
Challenge	WIP (13.00) – Controller (0.00)	-4.396	<0.001
	WIP (13.87) – Teleportation (3.00)	-4.240	<0.001
	Controller (9.19) – Teleportation (7.81)	-0.290	0.772
Negative Affect	WIP (13.28) – Controller (3.50)	-3.954	<0.001
	WIP (11.08) – Teleportation (7.67)	-2.008	0.045
	Controller (7.88) – Teleportation (9.96)	-2.396	0.017
Positive Affect	WIP (5.50) – Controller (9.67)	-1.565	0.118
	WIP (11.54) – Teleportation (14.86)	-0.028	0.978
	Controller (10.00) – Teleportation (7.17)	-1.638	0.101
Tiredness	WIP (13.33) – Controller (5.00)	-4.278	<0.001
	WIP (14.61) – Teleportation (4.50)	-3.669	<0.001
	Controller (6.50) – Teleportation (10.50)	-0.856	0.392

(iii) *Flow.* No statistically significant differences were found for the Flow component between the three techniques based on the Friedman test: $X^2(2) = 5.460, p = 0.065$.

(iv) *Tension.* The Friedman test indicated no statistically significant differences in the Tension component between the three techniques, $X^2(2) = 4.105, p = 0.128$.

(v) *Challenge.* The Friedman test indicated statistically significant differences for the Challenge component: $X^2(2) = 34.587, p < 0.001$. The post hoc analysis revealed a statistically significant difference for the Challenge score between WIP and Teleportation ($Z = -4.240, p < 0.001$), indicating that Teleportation is a less challenging technique than WIP (mean rank score 3.00). The WIP's and Controller's Challenge scores also presented statistically significant differences ($Z = -4.396, p < 0.001$), indicating that the controller-based technique is a less challenging technique than the WIP one.

Table 2: The results of the SUS survey for the examined VR locomotion techniques.

VR Locomotion Technique	Mean SUS Score (SD)	SUS Grade	SUS Rating
WIP	67.60 (16.58)	D	OK
Controller	84.33 (8.32)	B	borderline Excellent
Teleportation	82.69 (8.77)	B	Good

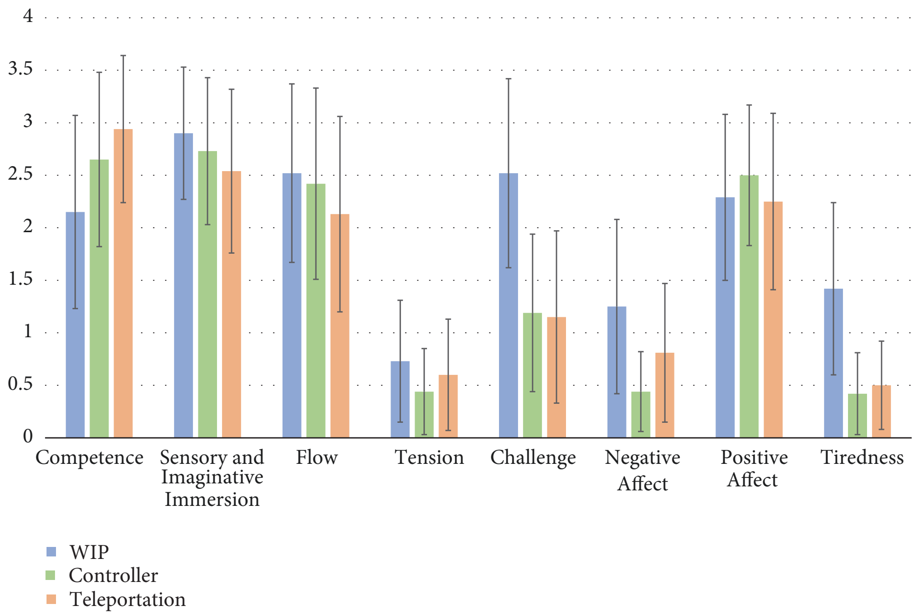

Figure 7: Mean GEQ values (with standard deviation bars) across eight experiential dimensions.

(vi) *Negative Affect.* The Friedman test indicated a statistically significant differences in the Negative Affect component: $X^2(2) = 15.459, p < 0.001$. The post hoc analysis for Negative Affect indicated statistically significant differences in all pair-wise comparisons. The Controller presented less Negative affect (mean score of 3.00) in the pair-wise comparison of WIP and Controller ($Z = -3.954, p < 0.001$). For the pair Teleportation and Controller ($Z = -2.396, p = 0.017$), the Controller-based VR locomotion again presented less Negative Affect, while for the pair WIP and Teleportation ($Z = -2.008, p = 0.045$), Teleportation scored lower values.

(vii) *Positive Affect.* The Friedman test indicated no statistically significant differences in the Positive Affect component between the three techniques: $X^2(2) = 1.268, p = 0.530$.

(viii) *Tiredness.* The Friedman test indicated statistically significant differences in the Tiredness component, $X^2(2) = 23.011, p < 0.001$. The post hoc analysis indicated statistically significant differences in pair-wise comparisons between WIP and Teleportation ($Z = -3.669, p < 0.001$) and between WIP and Controller ($Z = -4.278, p < 0.001$). In both cases, WIP presented significantly higher Tiredness scores than Teleportation and Controller, respectively.

4.6.2. SUS. The System Usability Scale survey produced the results of Table 2, which were based on the adjective ratings and grade scales described in [42, 62].

The Friedman test indicated statistically significant differences for the SUS values of the three techniques, $X^2(2) = 16.340$, $p < 0.001$. The post hoc analysis indicated statistically significant differences in the pair-wise comparisons between WIP and Controller ($Z = -3.833, p < 0.001$) and between WIP and Teleportation ($Z = -3.393, p = 0.001$). In both cases WIP presented significantly lower SUS values than the Controller and Teleportation techniques, respectively.

4.6.3. Interviews. Interrater reliability, regarding the coding of interview data by the two researchers, presented high agreement. Figure 8 presents the main interview remarks for each technique, visualised as stacked percentage bars.

Participants found WIP to offer high levels of immersion due to its natural and realistic way of moving. At the same time, many participants found that the translation of real body movement to VR motion made the technique tiresome. Others found this feature to add a certain level of physical training, fun, and entertainment. WIP also affected the balance of participants with no or limited VR experience at certain points during its use, causing motion-sickness; however, they were able to go on with the tasks. Finally, participants also reported the break of immersion in the virtual environment because of their fear of colliding with

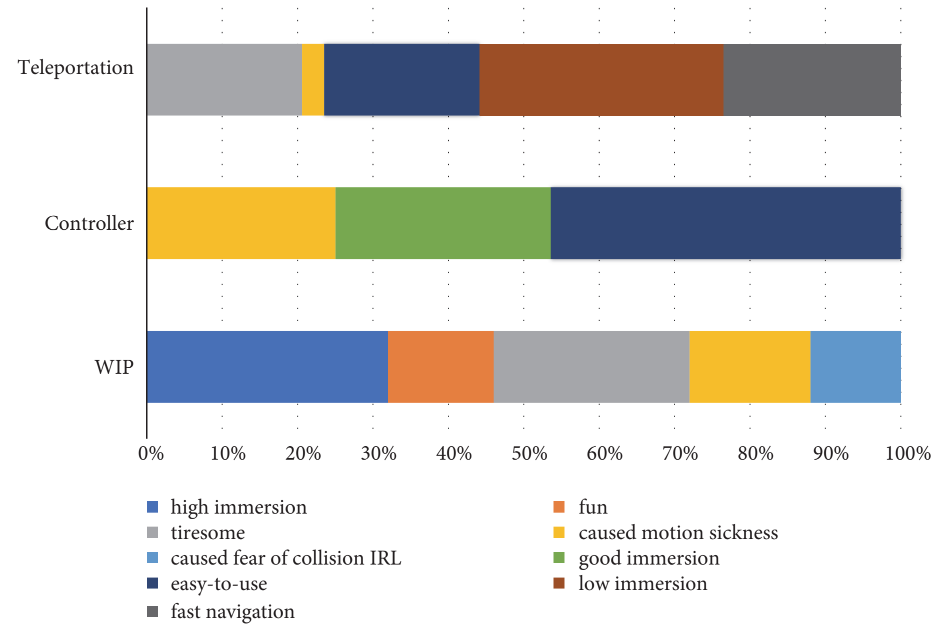

Figure 8: A summary of the VR locomotion techniques' qualities based on the participants' interviews.

physical objects in real life, despite the experimenters' taking all precautionary measures, i.e., having a virtual boundary system in place and an empty room.

Indicative participants' comments about walking-in-place:

(i) 'WIP was fun, and worked nicely while running. Gave a realistic feeling and much immersion. However, it was like exercising.' (Participant #13)

(ii) 'I always had to consider the real-life environment to not crash into objects. However, it was realistic and gave good immersion.' (Participant #3)

The controller/joystick VR locomotion was found to be easy-to-use and it has also been characterised as 'familiar', 'intuitive', and 'comfortable'. The previous experience that the participants had with controllers, e.g., game controllers, allowed them to immediately grasp the technique's functionality and master it, resulting in a comfortable navigation experience. It was also reported that during the first seconds of use, the technique caused motion-sickness (specifically balance loss); however, all the participants that reported motion-sickness also reported that it only took them a few seconds to adjust and master the technique. Moreover, the controller-based VR locomotion was reported to reach satisfying levels of immersion for participants.

Indicative participants' comments about controller/joystick:

(i) 'Joystick made me a bit dizzy in the beginning, but I got used to it. I liked it very well because it was familiar to gamepads, and easy to use.' (Participant #14)

(ii) 'Joystick was nice because I could walk freely while standing still. It was relaxing and I felt like having good control.' (Participant #19)

Teleportation was described as the least immersive of the three techniques, due to its visual 'jumps' and noncontinuous movement. 'Blinking'—the teleporting transition from one place of the virtual environment to another—also made the technique tiresome and put extra strain on the participants' vision, especially after many visual 'jumps'. Yet participants also found teleportation to be effective—when time is of the essence for the task—due to its fast navigation capabilities. Furthermore, using the method and mastering its interaction aspects were considered straight-forward and easy; the visual cues, i.e., the direction arc ray and marker on the virtual ground, were clear and understandable. Finally, only one participant reported slight motion-sickness for the initial use stages.

Indicative participants' comments about teleportation:

(i) 'Teleportation made my eyes very weary because it was blinking all the time. It was, however, very easy to use.' (Participant #21)

(ii) 'It's different because it was fast, and I felt like I had super-powers. However, it was the least immersive technique.' (Participant #6)

5. Discussion

In this section, the interaction qualities and experiential elements of the examined VR locomotion techniques, individually and comparatively, are discussed, along with the study implications and limitations.

5.1. Walking-in-Place. At first glance, the GEQ results revealed moderate-to-high values for WIP in negative dimensions, such as Tension, Challenge, Negative Affect, and Tiredness (Figure 7), while the SUS usability score was low (Table 2). The participants perceived the physical interaction of WIP in two opposite ways. On the one hand, constant physical movement made the technique tiresome; from time to time, the participants developed motion-sickness and fear of collision with physical objects. On the other hand, this physical interaction that is translated to virtual movement added an extra element of fun based on the participants' remarks (Figure 8) and, potentially, contributed to the moderate-to-high GEQ Positive Affect value. Furthermore, WIP scored high on the GEQ Immersion and Flow dimensions, thus highlighting its highly immersive nature, which was also confirmed by interview remarks. However, the participants clarified that the aforementioned motion-sickness and fear-of-collision issues deteriorated, at some points, the highly immersive state they were in during the session.

Most of the study's findings are consistent with the findings and indications from previous studies utilising WIP as a point of comparison for evaluating other techniques. The comparative studies of Bozgeyikli et al. [1, 30] capture the moderate-to-high values of WIP on immersion and enjoyment, and they document moderate-to-high values on tiredness, required interaction effort, and motion-sickness. The high perceived naturalness of the WIP technique—also praised by this study's participants during the interview sessions—has also been presented [15]. However, this study analysed these WIP qualities extensively in order to examine not only the performance of the technique but also how users experience it. Ultimately, the findings reveal that there is a strong connection between the WIP technique and the VR task. If users of WIP are aware of and have accepted the physical demands of the VR task before the session, then WIP can add certain levels of excitement, entertainment, and immersion in the task itself. Moreover, this study reported on the fear of collision with physical objects for WIP users, thus introducing and validating an important WIP issue.

5.2. Controller/Joystick. Controller/joystick provided an overall experience of good quality. The technique scored moderate-to-high values of GEQ Competence, Immersion, Flow, and Positive Affect (Figure 7); it also got a borderline Excellent in the SUS usability score (Table 2). Indeed, the participants found controller-based locomotion to be easy-to-use and master due to their previous experiences with game controllers, based on their interview remarks (Figure 8). At the same time, the effortless interaction with the technique allowed them to focus on the task and get immersed in the virtual environment. The fact that the technique was 'comfortable', based on the participants' comments, is further supported by the low values of GEQ Tension, Negative Affect, and Tiredness. However, the Challenge dimension presents a moderate value, which indicates that there was something challenging with the technique. The interviews revealed that some participants experienced motion-sickness during the first moments of the technique's use, but they were quickly adjusted to the movement.

Previous comparative studies using the controller/joystick technique as a point of comparison have provided indications about the qualities described herein. The technique has been shown to provide satisfying levels of immersion and flow [1, 30] and be easy-to-use and master [1, 25, 30, 66]. This study explored the reasons behind controller-based VR locomotion being easy-to-use and quasi-groundtruth when it comes to its use for comparatively evaluating newly constructed techniques. Participants' feedback revealed that their previous experience with game controllers in other, non-VR settings provides a high sense of mastery and familiarity with the technique.

Motion-sickness is an interaction issue of the controller/joystick technique that has been documented in the literature [1, 30, 66]. In this study, the quick adjustment of participants to the technique's settings was reported; immersion and flow were not interrupted, and their high levels were preserved. This finding potentially justifies and explains findings of previous studies for the controller/joystick that reported both considerable motion-sickness levels and moderate-to-high immersion levels.

5.3. Teleportation. Teleportation's performance was close to the controller; however, it presented some unique differences. On the positive side, the technique demonstrated good usability; the users praised its ease-of-use and its effectiveness for accomplishing their tasks through fast navigation. These observations are also evident from the moderate-to-high values of the GEQ Competence and Positive Affect dimensions, the low values of Challenge (Figure 7), as well as the 'good' SUS score (Table 2). Very low values of self-reported motion-sickness were documented through the interviews (Figure 8). On the negative side, teleportation showed a moderate performance of both GEQ Immersion and Flow values; the users stated in the interviews that teleportation provided low immersion due to its noncontinuous motion. Moreover, the moderate GEQ Challenge values in combination with the low-to-moderate Negative Affect and the considerable Tiredness values may present an interaction-related issue. The users reported feeling tired because of the technique's teleporting visual 'jumps'. Naturally, this issue did not stop them from using and mastering the technique and fulfilling their goals; nevertheless, it had a negative effect on their overall experience.

Previous studies on teleportation have demonstrated that it can provide a positive VR experience [1, 66, 69, 70] while offering ease-of-use and control for users [1, 30, 66]. This work highlighted the sense of accomplishment, effectiveness, and competence that teleportation can offer through potentially fast navigation. At the same time, it addressed the indication of discomfort regarding teleportation that was found in a previous user study [70]. In this study, this element was attributed to tiredness because of the eye strain caused by the visual 'jumps', which also resulted in breaking the users' immersion.

5.4. Comparison of Techniques. When comparing the three prevalent VR locomotion techniques, several observations can be made. The users found WIP to offer the highest immersion of the three; the controller/joystick performed satisfactorily, and teleportation was at the low end (Figure 8). This is also supported by the examination of GEQ Immersion and Flow values (Figure 7) with the former presenting statistically significant differences (Table 1). Teleportation and Controller/joystick presented low Challenge values and high SUS scores (Table 2), which confirmed the users' positive observations about the ease-of-use. However, WIP was considered to be a physically demanding interaction technique creating psychophysical discomfort, i.e., fear of collision, motion-sickness, and tiredness; thus, it scored low on the SUS and presented statistically significant high values in the GEQ dimensions of Challenge, Negative Affect, and Tiredness. Controller/joystick presented the highest self-reported motion-sickness values; however, the temporary nature of this phenomenon did not allow it to be clearly visible in the GEQ values. Regarding competence and sense of effectiveness, Teleportation and Controller/joystick performed better than WIP, with teleportation presenting a slight advantage due to its fast navigation capabilities. Finally, all of the techniques presented similar, moderate-to-high GEQ Positive Affect values, which potentially signify that each technique carries its own characteristics, strengths, and weaknesses that if recognised and addressed appropriately can lead to a positive VR experience.

5.5. Study Implications. Researchers and developers in the field can benefit from this study, as they can gain insights into matters of methodology, theoretical knowledge, and future research directions for VR locomotion.

Through this work, an effective methodology for comparing VR locomotion techniques was presented. The prevalent techniques were identified based on research-related criteria, originating from the reviewed and studied VR locomotion techniques of the last four years. This provided an up-to-date character to the examined VR locomotion techniques and their implementation. Moreover, a mixed methods approach was utilised, following top-down logic. Through the UX and usability questionnaires, the users provided an overview of the techniques' usability performance and experiential qualities. The interviews focused more deeply on the techniques' characteristics and the specific reasons influencing the users' experiences. The study results supported previous findings and produced new knowledge on specific experiential attributes of the examined techniques. These can lead to certain research directions:

(i) Physical activity in WIP can be tiresome; however, if it is presented within an appropriate task or concept, like in a VR game for physical exercise [71], WIP can be suitable and greatly beneficial as a VR locomotion technique. Moreover, the WIP users' fear of collision with physical objects is an experiential issue that needs further examination and tackling in future research.

(ii) The ease-of-use for controller/joystick VR locomotion due to the users' familiarity with controllers can be the trigger for further research on the interaction-related learning effect that the VR users carry with them from non-VR to VR settings and its impact on the way that VR locomotion is experienced. Furthermore, motion-sickness is still a problematic interaction aspect of controller-based VR locomotion and effective technical solutions are needed, just like the dynamic field-of-view adjustment (blinders) [67].

(iii) From an interaction perspective, teleportation may benefit by addressing the noncontinuous motion characteristic. A feasible approach would be to implement the teleportation techniques with continuous motion and to use 'grabbed' points and 'anchors' in the virtual environment, like point-tugging [66]. This way, the users could select the point where they want to teleport to; the motion towards that point would then be continuous, 'locked', and at increased or user-adjustable speed. Naturally, by introducing continuous motion in teleportation, there may be gains in terms of immersion and reduced eye strain; however, the balance between motion speed and motion-sickness should also be considered.

Through the interviews and based on the GEQ and SUS analysis, the study overall highlighted the main dimensions for capturing comparative experiences with VR locomotion techniques. When they were asked open questions about the compared techniques, the participants chose to focus on specific subjects, which provided strong indications regarding which interaction aspects UX analysis should cover when comparing VR locomotion techniques. A list of these dimensions and brief definitions, based on the participants' feedback, are presented as follows.

(i) *Immersion and flow*, i.e., the degree to which the technique supports the users' attention in the virtual task and environment and alters their sense of space, time and self. For instance, in this study, WIP demonstrated higher degrees of immersion and flow compared to the other techniques due to the exact translation of real motion into virtual motion.

(ii) *Ease-of-use and mastering*, i.e., the degree to which operating the technique can be learned and can enable efficient navigation. For instance, in this study, the controller/joystick VR locomotion technique was considered to be very easy-to-use and master, mostly due to the participants' previous experiences with controllers.

(iii) *Competence and sense of effectiveness*, i.e., the degree to which the technique can assist the users in accomplishing their goals and tasks. In this case, teleportation was presented as the most effective technique, enabling the users to move quickly and accomplish their tasks.

(iv) *Psychophysical discomfort*, i.e., the degree to which the technique causes fear, motion-sickness, and tiredness. In this study, WIP caused fear of collision, motion-sickness, and tiredness because of the intense physical activity (Figure 8). However, immersion was not interrupted to a great degree. Teleportation caused eye strain, which broke immersion, while controller/joystick caused motion-sickness in the early use stages.

Researchers can benefit from focusing on these dimensions when comparing VR locomotion techniques, although more research is necessary in order to produce tools that accurately measure them in this specific context.

5.6. Study Limitations. The current study has certain limitations. The VR locomotion techniques were implemented in their basic form following established motion speed and latency settings as presented by literature [25, 28, 29, 33, 36, 37, 72] and VR manufacturers [36], and without any add-ons, such as 'blinders' [67], which could have had a positive effect on the overall experience. The decision to only use the basic form was based on the assumption that the prevalent techniques should be evaluated based on the most traditional implementations that researchers and users usually come across and that game engines enable developers to implement. To further support that decision, room-scale-based VR locomotion (real-walking) was integrated in all three evaluated techniques, whereas special locomotion styles, such as climbing, flying, or swimming, were not implemented.

Regarding the virtual tasks the users had to perform, there were not set courses for accomplishing the tasks and getting to the checkpoints; therefore, no task-completion time comparisons were carried out. The reason for that decision was to give users the time to experience the environment any way they wanted while having an interaction goal that served them. The study was focused on experiential, qualitative, and user-centred elements; therefore, the comparison of the techniques by task-completion time was not taken into account nor examined.

Another limitation of this study is the sample profile regarding age. The user recruitment process led to a participant sample of a young age (mean age: 25.96, SD: 5.04), probably because of the study's modern technological theme and its appeal to younger audiences. The degree of the study participants' previous experiences with VR and other hardware, e.g., controllers, may have been affected by their young age. Although the target population of VR applications is young, it could be interesting to evaluate these VR locomotion experiences with an older population, since VR devices are beginning to reach every type of profile [73].

Finally, low-end, immersive VR headsets utilising mobile devices (such as Google Cardboard and Samsung Gear VR) were not used in this study. This decision was based on previous implementations of VR systems found in literature [5] as well as on the fact that in this study, a highly immersive VR experience was targeted so that users could have a representative VR locomotion experience.

6. Conclusion

The presented comparative study has shed more light on the new era of VR locomotion, analysing the user experience coming from prevalent VR locomotion techniques and promoting these techniques from points of comparison for benchmarking purposes to central study objects for future design inspiration and guidance. The study managed to (i) document the interaction attributes of these techniques from an experiential and user-centred point-of-view, (ii) present the implications these findings can have on future techniques' designs, and (iii) identify the main interaction dimensions that the users focus on when describing and comparing VR locomotion experiences. Results showed that the three evaluated techniques—walking-in place, controller/joystick, and teleportation—are different in many interaction aspects, each one having its own characteristics, strengths, and weaknesses. Furthermore, the VR locomotion users tend to focus on issues of immersion, ease-of-use, competence, and psychophysical discomfort when describing and evaluating their experiences with the techniques. Overall, the study provides researchers, developers, and practitioners in the field with much interaction-related information regarding the evaluated and compared VR locomotion techniques, so that they are able to base their future designs or conceptual models on solid empirical and theoretical knowledge.

Future work will address each VR locomotion technique's design implications and improvements (Section 5.5). Moreover, further investigations will be conducted on developing a research tool, specifically tailored for evaluating VR locomotion experiences and measuring the four interaction dimensions the users focus on.

Data Availability

Data used to support the findings of this study are restricted by legal rights and institutional policies. Data are available from the corresponding author upon request, for researchers who meet the criteria for access.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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