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Locomotion in Place in Virtual Reality: A Comparative Evaluation of Joystick, Teleport, and Leaning

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Abstract—Recent VR head-mounted displays for consumers feature 3-DOF or 6-DOF head tracking. However, position tracking (when available) is limited to a small area. Moreover, in small or cluttered physical spaces, users can safely experience VR only by staying in place, standing or seated. Different locomotion techniques have been proposed to allow users to explore virtual environments by staying in place. Two in-place locomotion techniques, frequently employed in the literature and in consumer applications, are based on joystick and teleport. Some authors explored leaning with the aim of proposing a more natural in-place locomotion technique. However, more research is needed to understand the effects of the three techniques, since no user study thoroughly compared them all together on a variety of fundamental aspects. Therefore, this paper presents a comparative evaluation with 75 users, assessing the effects of the three techniques on performance, sickness, presence, usability, and different aspects of comfort. Performance of teleport was better than the other techniques, and performance of leaning was better than joystick. Teleport also caused less nausea than the other techniques. Unexpectedly, no significant differences were found for presence. Teleport received a higher usability score than the other techniques. Finally, the techniques had different effects on comfort that we discuss in detail.

Index Terms—Immersive virtual reality, locomotion techniques, teleport, joystick, leaning, user study, comparative evaluation

1 Introduction

NAVIGATION in virtual environments (VEs) consists of two different tasks: (i) *wayfinding*, i.e. "the cognitive process of determining a path based on visual cues, knowledge of the environment, and aids such as maps or compasses" [1], and (ii) *travel*, i.e., "the control of the user's viewpoint motion in the three-dimensional environment" [1]. Travel is "one of the most basic and universal interactions found in VE applications" [1], so it received considerable attention since the '90s [1], [2], [3], [4]. Recently, new virtual reality (VR) head-mounted displays (HMDs) for consumers have been released, and different authors started to study travel using these new HMDs [5], [6], [7], [8], [9], [10]. Since all these HMDs feature at least 3-DOF head tracking, head orientation can be used to control users' orientation in the VE. Position tracking is instead available only with HMDs featuring 6-DOF tracking, and is anyway limited to a small area. Moreover, in small or cluttered spaces, users can safely experience VR only by staying in place, standing or seated.

Virtual *locomotion* techniques are interaction techniques for allowing a user to move over long distances in a VE, while remaining in a relatively small physical place [4]. Different locomotion techniques have been proposed, and some of them can be used in place. Two in-place locomotion techniques frequently employed in the literature as well as in consumer VR applications are respectively based on joystick and teleport. In *joystick*, users press directional buttons, sticks or pads to continuously move the viewpoint in the chosen direction. In *teleport*, users point to a destination (e.g., with a tracked handheld controller) and confirm it (e.g., by pressing a button) to instantly move the viewpoint there [6], [7], [10], [11]. To propose a more natural in-place locomotion technique, some authors explored *leaning*, allowing users to physically lean in the desired direction of movement [8], [9], [12]. Other authors explored specific hardware (e.g., special treadmills) [13], or techniques that require users to walk in place [2], [14], [15], [16] or in a small area (e.g., redirected walking) [17], [18]. In this paper, we focus on in-place techniques that can be used both standing and seated, and are supported by current HMDs with 6-DOF tracking of both user's head and handheld controllers. Therefore, we concentrated on joystick, teleport, and leaning.

To the best of our knowledge, no user study thoroughly compared all three techniques together on a variety of aspects that play a fundamental role in the VR experience. Indeed, while several studies focused on performance (e.g., in terms of time to complete a given travel task), other aspects such as sickness, presence, usability, and comfort were assessed less often, on a subset of the three techniques, and with a small sample of users. Therefore, this paper presents a comparative evaluation of the effects of joystick, teleport, and leaning on performance, sickness, presence, usability, and different aspects of comfort, on a

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sample of 75 users.

The paper is organized as follows. Section 2 summarizes previous studies that compared the effects of joystick, teleport, and leaning, as well as those that compared them with other techniques that can be used in place. Section 3 describes how the three considered techniques were used in our study. Section 4 describes the study, while Sections 5 and 6 respectively report and discuss the results. Finally, Section 7 concludes the paper outlining future work.

2 Related Work

Several studies assessed the effects of locomotion techniques in immersive VR. Since the focus of this paper is on joystick, teleport, and leaning with HMDs, this section describes studies concerning these techniques, including those that compared at least one of the three techniques with other in-place techniques based on HMDs. Therefore, it does not include studies that did not use HMDs (e.g., studies conducted in a CAVE as in [19]), and studies that tested different locomotion techniques with different hardware (e.g., those that tested some techniques with an HMD and others with a desktop monitor in the same study as in [20], [21]), because the change in hardware could have affected the results. Table 1 summarizes the considered studies, specifying the techniques that were compared (only those related to our focus), sample size, performed tasks, dependent variables, and main findings related to our focus.

Different studies implemented the techniques in different ways using the same names or called similar techniques with different names. For example, with HMDs and head tracking, joystick is often used to control only the translation [5], [8], [10], [12], [22], because rotation can be detected by the head tracker and users can rotate while standing in place or seated on a swivel chair. However, joystick can also be used to control both translation and rotation [8], [9], as common in videogame consoles. Some authors use the term joystick to indicate the former case [5], [10], [12], while others use the same term to indicate the latter [8], [9]. To avoid confusion, we use *joystick translation & real rotation* (JT&RR) to indicate the former, and *joystick translation & joystick rotation* (JT&JR) to indicate the latter. Teleport is often controlled by pointing at the desired destination (e.g., with a tracked handheld controller), and thus it is sometimes called *point & teleport* (P&T) [11], [23]. In some implementations, users cannot point everywhere they would like, but can instead choose among a fixed set of predefined teleport points. In this case, the technique is sometimes called *fixpoint teleport* (FPT) [7]. Finally, users can also be teleported by the system to a predefined destination [3]. We indicate this implementation of teleport as *automatic teleport* (AT). The different implementations of leaning share the basic idea that users should just lean in the direction they wish to travel to, and the speed of movement is determined by how much they lean [24]. The first implementations based on head tracking [24], [25] and an implementation based on a Wii Fit Balance Board [12] are examples of *leaning from a standing position* (LSP). Leaning was also implemented for users seated on a common swivel chair (*leaning on a swivel chair*, LSC) [8], [9] or on a special stool that can rotate and lean (*leaning on a special stool*, LSS) [8], [9]. Finally, *head tilt* (HT) can be considered as an implementation of leaning in which the viewpoint is moved forward/backward according to head pitch and rotated according to head yaw [9], [26].

No study compared all three techniques (joystick, teleport, and leaning) together. Hashemian and Riecke [8] compared two implementations of leaning (LSC and LSS) with two implementations of joystick (JT&RR and JT&JR). Kitson et al. [9] compared four implementations of leaning (LSC, two implementations of LSS with different stools, and HT) with JT&JR. Harris et al. [12] compared LSP with JT&RR, and with the *walk-in-place* (WIP) technique, in which the viewpoint is moved forward when users perform steps in place. Tregillus et al. [26] compared HT with JT&RR as well as with WIP-Tilt (WT), a combination of HT to control rotation and WIP to control translation. McCullough et al. [5] compared JT&RR with a variant of WIP called *arm swinging* (AS), in which the viewpoint is moved forward when users move the arms to simulate walking. Lee et al. [22] compared a variant of JT&RR, in which the viewpoint is moved according to head direction when users press a button on the joystick, with three different techniques: (i) *push & go* (PS&G), in which the viewpoint is moved according to the physical movement of a tracked joystick when users push a button, (ii) *point & go* (PN&G), in which the viewpoint moves towards the destination pointed by users, and (iii) *grab & drag* (G&D), in which the VE is moved according to the movement of a tracked joystick when users push a button. Bozgeyikli et al. [11] compared JT&RR with P&T and WIP. A recent study by the same authors [23] added five techniques to the comparison. Two of them can be used in place without additional hardware: *hand flapping* (HF), in which the viewpoint is moved forward when users flap their hands, and *flying* (FL), in which forward motion of the viewpoint is started and stopped by raising a hand. Langbehn et al. [10] compared JT&RR with P&T and an additional technique that cannot be used in place (redirected walking). Frommel et al. [7] compared JT&RR, P&T, FPT, and a locomotion technique in which the viewpoint is automatically moved towards a predefined destination (we indicate it as *automatic movement*, AM). Christou and Aristidou [6] compared P&T with *hand pointing* (HP), in which the viewpoint is moved in the direction pointed by users with a tracked hand-held device, and *head-directed steering* (HDS), in which the viewpoint is moved in the direction faced by user's head. Bowman et al. [3] compared AT with AM.

Regarding the number of participants, the largest sample was recruited by Lee et al. [22] (98 participants). Tregillus et al. [26], Frommel et al. [7], and Langbehn et al. [10] recruited, respectively, 25, 24, and 33 participants (with 22 of them trying in-place locomotion techniques). The remaining studies all involved small samples (16 or less participants), so the lack of statistical significance in some of the results might be related to the small sample.

TABLE 1
COMPARISONS OF LOCOMOTION IN PLACE TECHNIQUES

Reference	Techniques*	Sample size	Tasks	Dependent variables	Main findings
Bowman et al. (1997) [3]	AM, AT	10	Locate a target after being moved to a different position	Time to find the target (spatial orientation)	Less time with AM than AT
Lee et al. (2009) [22]	JT&RR, PS&G, PN&G, G&D	98	Reach and touch 10 waypoints within 3 minutes	Travel speed, reach time (time to touch a waypoint after reaching it), path efficiency (users' path / shortest path), overshoot (number of times users reach a waypoint without touching it)	Best travel speed with G&D; worst travel speed with PS&G; best path efficiency with PN&G; better path efficiency with JT&RR than G&D; no significant differences in reach time and overshoot
Harris et al. (2014) [12]	LSP, JT&RR	10	Remember the location of 6 targets, move to a new position, turn towards a target without vision	Time and error in degrees to turn towards the target (spatial orientation)	Larger error with JT&RR; no significant differences in time
Harris et al. (2014) [12]	LSP, WIP	12	Remember the location of 6 targets, move to a new position, turn towards a target without vision	Time and error in degrees to turn towards the target (spatial orientation)	No significant differences in error; less time with WIP than LSP
McCullough et al. (2015) [5]	AS, JT&RR	12	Remember the location of 6 targets, move to a new position, turn towards a target without vision	Time and error in degrees to turn towards the target (spatial orientation)	Larger error with JT&RR than AS; no significant differences in time
Bozgeyikli et al. (2016) [11]	P&T, WIP, JT&RR	16	Reach 10 destinations (6 on a VE without obstacles, 4 in a VE with obstacles)	Time to reach destinations, collisions with obstacles, usability, effort, sickness, presence, ranking of techniques	Less time with JT&RR and P&T than WIP with no obstacles; less time with JT&RR than WIP and P&T with obstacles; less collisions with P&T than WIP and JT&RR; more difficulty to understand with WIP than JT&RR; more effort and tiredness with WIP than JT&RR and P&T; no significant differences in sickness, presence, and preference
Christou and Aristidou (2017) [6]	HDS, HP, P&T	15	Travel from a start position to a destination shown on a map, collecting tokens during the path	Successful trials (trials in which the destination was reached), time to reach destination, collected tokens, sickness	Less successful trials with HP than HDS and P&T; less time with P&T than HDS and HP; more collected tokens with HP and HDS than P&T; more sickness with HP than P&T
Frommel et al. (2017) [7]	P&T, FPT, JT&RR, AM	24	Explore a virtual zoo for 5 minutes	Sickness, presence, enjoyment, valence, arousal, and dominance	Less nausea with P&T than AM; less ocular-motor symptoms with P&T than JT&RR; less overall sickness with P&T than JT&RR; higher presence with P&T than FPT and AM; higher enjoyment with P&T than JT&RR and AM; higher enjoyment with FTP than AM; higher valence with P&T than JT&RR and AM; higher dominance with P&T than AM; no significant differences with the other variables
Hashemian and Riecke (2017) [8]	JT&JR, JT&RR, LSC, LSS	14	Follow an avatar on a curvilinear path	Accuracy, sickness, presence, intuitiveness, precision of control, ease of use, comfort, reported problems, overall usability	Less accuracy with LSS than JT&JR and JT&RR; best precision of control with JT&JR; more comfort, less problems and more overall usability with JT&JR than LSS; no significant differences with the other variables
Kitson et al. (2017) [9]	JT&JR, LSS, HT, LSC	16	Search for objects in a virtual city	Ratings about comfort, ease of use, precision of movement, spatial orientation, sensation of self-motion, problems, presence, enjoyment, overall usability, sickness	More comfort, ease of use, precision of movement, spatial orientation and less reported problems with JT&JR than the other techniques; no significant differences with the other variables
Tregillus et al. (2017) [26]	HT, WT, JT&RR	25	Run through five large virtual corridors without hitting obstacles	Sickness, time to complete the task, number of collisions, ratings about efficiency, learnability, likability, and presence	Less time and less collisions with HT than JT&RR; less time with HT than WT; higher likeability and presence with HT than JT&RR; higher efficiency, learnability, and likeability with HT than WT; no significant differences in sickness
Langbehn et al. (2018) [10]	JT&RR, P&T	22	Navigate through 5 targets in a virtual room, point at the targets without seeing them, estimate room size without vision, draw a map of the room on a piece of paper, arrange objects seen in the room on a paper map	Error in degrees to point at the targets (spatial orientation), error in room size estimation, map drawing score, arranged object distances from correct position, object arrangement score, sickness, presence, liking of the techniques, time to complete the task	Larger error to point at one of the targets with JT&RR than P&T; more sickness with JT&RR than P&T; higher liking with P&T than JT&RR; no significant differences between JT&RR and P&T with the other variables
Bozgeyikli et al. (2019) [23]	WIP, P&T, JT&RR, HF, FL	15	Reach 10 destinations (6 on a VE without obstacles, 4 in a VE with obstacles)	Time to reach destinations, collisions with obstacles, user experience (difficulty in understanding and in operating, feeling of being in control, enjoyment, required effort, tiredness, overwhelmedness, frustration), sickness, presence, preference score	Less time with P&T and JT&RR than WIP, HF and FL, and less time with WIP than FL with no obstacles; less time with JT&RR than WIP, P&T and HF, and less time with FL than WIP, P&T and HF with obstacles; less collisions with P&T than WIP, JT&RR, HF and FL; significant differences for all user experience aspects except overwhelmedness, but no statistical analysis of pairwise comparisons; no significant differences in sickness; overall significant differences in presence, but no statistical analysis of pairwise comparisons; highest preference score for P&T, lowest for HF

**AM=automatic movement, AS=arm swinging, AT=automatic teleport, FL=flying, FPT=fixpoint teleport, G&D=grab & drag, HDS=head-directed steering, HF=hand flapping, HP=hand pointing, HT=head tilt, JT&JR=joystick translation & joystick rotation, JT&RR=joystick translation & real rotation, LSC=leaning on a swivel chair, LSP=leaning from a standing position, LSS=leaning on a special stool, P&T=point & teleport, PN&G=point & go, PS&G=push & go, WIP=walk-in-place.*

Tasks that participants had to perform varied with study goals. For example, in studies that assessed locomotion performance or that considered several different variables, the task typically consisted in reaching a destination, possibly after going through different waypoints [6], [11], [22], [23]. Studies that focused instead on spatial orientation typically asked participants to remember the location of some targets or navigate through them, travel to a new position, and finally turn towards or point at the targets without seeing them [5], [10], [12].

Performance metrics (e.g., time to reach or look at a target) were assessed in the majority of studies [3], [5], [6], [8], [10], [11], [12], [22], [23], [26]. Sickness was assessed in [6], [7], [8], [9], [10], [11], [23], [26], presence in [7], [8], [9], [10], [11], [23], [26], and some aspects of usability and comfort in [8], [9], [11], [23], [26].

Considering locomotion performance, P&T was faster than HP and HDS [6], and JT&RR was faster than WIP [11], [23] and HF [23]. P&T was faster than WIP [11], [23], HF [23], and FL [23] if there were no obstacles in the VE, and slower than JT&RR [11], [23] and FL [23] if there were obstacles. With no obstacles, JT&RR was faster than FL [23]. HT was faster than JT&RR and WT [26], and caused less collisions than JT&RR [26]. P&T caused less collisions than JT&RR [11], [23], WIP [11], [23], HF [23], and FL [23]. Considering spatial orientation, JT&RR led to larger error than LSP, and LSP required more time than WIP [12]. JT&RR led also to larger error than AS [5] and P&T [10]. The only significant results found for sickness were that P&T caused less sickness than HP [6] and JT&RR [7], [10]. P&T caused also less nausea than AM [7] and less oculomotor symptoms than JT&RR [7]. No statistically significant results were found for presence except for an overall significant difference between all the techniques considered in [23], which reported no statistical analysis of pairwise comparisons, a higher presence with P&T than FPT and AM in [7], and a higher presence with HT than JT&RR in [26]. Both JT&RR and P&T required less effort and caused less tiredness than WIP [11]. JT&RR was also easier to understand than WIP [11]. Learnability, efficiency, and likeability were higher with HT than WT [26]. Enjoyment was higher with P&T than JT&RR and AM [7] and higher with FPT than AM [7]. In [23], JT&RR and P&T were among those that were less difficult to understand, provided higher levels of enjoyment, required less effort to operate, and caused less tiredness and frustration. JT&RR was also one of the least difficult to operate and one of best to provide the feeling of being in control. However, while the overall differences reached significance, no statistical analysis of pairwise comparisons was reported. Finally, some advantage of JT&JR over LSC and LSS, and over HT emerged from the studies that assessed some additional aspects of usability and comfort [8], [9].

Overall, locomotion techniques have been widely studied in the literature, but no study compared all three techniques (joystick, teleport, and leaning) together. Moreover, most studies involving one or two of the three techniques involved small samples, and the studies mainly found statistically significant results for performance metrics, while additional studies are needed to better understand the effects of different locomotion techniques on sickness, presence, usability, and comfort.

3 Considered Locomotion Techniques

As mentioned in the introduction, we decided to focus on joystick, teleport, and leaning techniques because none of them need special hardware in addition to an HMD with 6-DOF tracking of head and handheld controllers, and all of them can be used in place, both standing and seated. For safety reasons, the implementation of the techniques described below supported users seated on a swivel chair that allowed for 360 degrees of rotation.

All three techniques allowed users to control rotation by means of the head tracker, and differed only in the way users controlled viewpoint translation:

1. Joystick relied on the touchpad available on handheld controllers. Users could touch the upper area of the pad to move forward in the direction of sight, the lower area to move backwards, and left and right areas to strafe (Fig. 1A). If users touched the pad on the overlap of two areas (e.g., upper left), the viewpoint moved in a diagonal way. This joystick technique is an implementation of JT&RR.
2. Teleport relied on the 6-DOF tracking of the handheld controllers and on the touchpad that could be pressed as a button. When users pressed the button, a ray beamed from the handheld controller in the VE. The ray was represented as a dotted arc and the position in which the ray hit the ground was highlighted with a halo (Fig. 1B). Users could move the handheld controller to indicate a position on the ground with the ray and release the button to be teleported there. This teleport technique is an implementation of P&T.
3. Leaning relied on the 6-DOF tracking of the head. Users could lean their torso forward to move forward, backwards to move backwards, and left and right to strafe. If users leaned in two directions simultaneously (e.g., forward left), the viewpoint moved in a diagonal way. The resting position of the head was calibrated for each user after inviting him/her to sit on the swivel chair with the back straight and the head facing forward. The larger

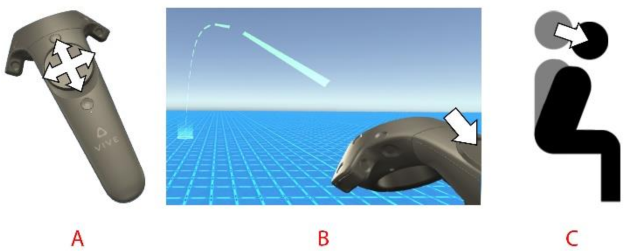


Fig. 1. The considered locomotion techniques: a) joystick, the white arrows represent the main interactions with the pad, b) teleport, the white arrow indicates the button to press, the dotted arc is the ray and the halo indicates the destination position, and c) leaning, the white arrow indicates the distance between the maximum speed position (in black) and the resting position (in gray).

was the distance between current position of the head and its resting position (Fig. 1C), the higher the speed of movement. To avoid involuntary movements, we set a minimum distance (5 cm) under which the viewpoint was not moved. We also set a maximum distance (30 cm) above which the speed did not increase to prevent users to excessively lean to move faster. This leaning technique is an implementation of LSC.

4 User Study

To evaluate the considered in-place locomotion techniques, we carried out a between-groups user study. In the following, we will refer to the group of participants who tried joystick as Joystick (J) group, those who tried teleport as Teleport (T) group, and those who tried leaning as Leaning (L) group.

4.1 Hypotheses

We formulated the following hypotheses:

1. Performance (in terms of time to complete a given travel task) could be better in the Teleport group because the instantaneous movement of the viewpoint can save time with respect to the continuous movement of the other techniques.
2. Sickness could be higher in the Joystick group because the viewpoint moves continuously while users' head is still, and the sensory conflict between visual and vestibular systems can cause sickness [27]. The conflict is not present using teleport, because the viewpoint moves instantaneously to the destination, and might be attenuated with leaning, because users move their head in the same direction of the viewpoint.
3. Presence could be lower in the Teleport group because teleporting is very different from the real-world experience of moving and this might break the sense of being in the VE. On the contrary, joystick and leaning allow for a continuous locomotion in the VE that resembles more the way people move in the real world.
4. Users could learn how to use joystick more easily because they could be already familiar with joysticks in videogames. The study was instead exploratory about other aspects of usability.
5. The Leaning group could spend more physical effort and suffer spine fatigue more than the other two groups because leaning requires users to bend their torso. The study was instead exploratory about other aspects of comfort.

4.2 Materials and Tasks

The study employed two VEs: a tutorial VE that allowed users to familiarize with the locomotion techniques (Fig. 2A and B) and a VE for the assessment of performance on a travel task (Fig. 2C, D and E). The tutorial VE was a simple rectangular plane field delimited by four walls. The only initial object in the field was a barrel, indicated with "Barrel 1" in Fig. 2A. Participants were invited to travel from "Start" position to "Barrel 1", and then to "Barrel 2" and "Barrel 3", which appeared only when the previous barrel was reached. Reached barrels were automatically removed from the VE, so at each time only one barrel was present. When "Barrel 3" was reached, "Barrel 1" appeared again, and the sequence restarted.

The VE for the assessment of performance was a bigger and more complex plane field delimited by walls. The VE contained trees, benches, rocks and buildings. In this VE, barrels appeared in eleven different positions ("Barrel 1" to "Barrel 11" in Fig. 2C). Participants' task consisted in traveling from "Start" to "Barrel 1", and then to the following barrels, each of which appeared only when the previous one was reached. Reached barrels were automatically removed from the VE. The task ended when "Barrel 11" was reached.

Since the focus of this study was on travel and not on wayfinding, the direction in which participants should go to reach the next barrel was indicated in both VEs by an arrow, as shown in Fig. 2B, D and E.

The VEs were implemented using the Unity 5.6 game engine and run on a PC equipped with a 3.60 GHz Intel i7-4790 processor, 16 GB RAM, and a NVidia GTX 970 graphic card. The HMD was an HTC Vive with its handheld controllers.

4.3 Participants

The evaluation involved a sample of 75 participants (68M, 7F). They were undergraduate students in computer science. Age ranged from 20 to 26 (M=21.68, SD=1.52).

We asked participants to rate their familiarity with the use of joysticks (e.g., Xbox and Playstation controllers) for playing 3D videogames on a 7-point scale (1 = no familiarity, 7 = high familiarity). Answers ranged from 1 to 7 (M=5.67, SD=1.66). We used the same scale to ask participants about their familiarity with systems that detect body movements (e.g., Kinect and Wiimote) in 3D videogames. Answers ranged from 1 to 7 (M=3.64, SD=1.67).

We also asked participants if they had ever used HMDs: 34 participants had used them and the remaining 41 had not. Participants who had used HMDs were asked for how much time they had used them. Answers received ranged from 10 minutes to 10 hours (M=1.32 hours, SD=1.79). These participants also rated their familiarity with joysticks (e.g., HTC Vive and Oculus Rift controllers) and systems that detect body movements (e.g., HTC Vive and Oculus Rift trackers) in an immersive VR context on a 7-points scale (1 = no familiarity, 7 = high familiarity). Answers ranged from 1 to 7 for joysticks (M=2.09, SD=1.42) and from 1 to 5 for systems that detect body movements (M=2.32, SD=1.49).

Participants were assigned to the three groups in such a way that: (i) each group had 25 participants (23M, 2F in the J and T groups; 22M, 3F in the L group); (ii) the three groups were similar in terms of age, familiarity with the use of joysticks and of systems that detect body movements for playing 3D videogames, time of previous use of HMDs, and familiarity with the use of joysticks and of systems that detect body movements in an immersive VR context. Each of these variables was submitted to a one-way ANOVA that confirmed the lack of significant differences between the three groups.

4.4 Measures

4.4.1 Performance

Performance was measured in terms of time to complete the travel task described in Section 4.2. More precisely, we logged the seconds elapsed from the instant participants began at the "Start" position in the VE (Fig. 2C) to the instant they reached "Barrel 11" after going through the sequence of all the other barrels.

4.4.2 Sickness

To assess sickness in participants, we asked them to rate how much they were affected by four symptoms after they completed the travel task (post-test) and we subtracted the ratings they gave before the experimental condition to the same symptoms (pre-test). The symptoms were four essential items (1, 3, 4 and 8) of the Simulator Sickness Questionnaire (SSQ) [28]: (i) general discomfort, (ii) headache, (iii) eye strain, and (iv) nausea. Participants rated how much each symptom affected them at the time of questionnaire completion on a 4-point scale (1 = none, 2 = slight, 3 = moderate, 4 = severe). We did not use the other SSQ items because we wanted to minimize the negative influence of pre-test compilation of SSQ that could affect participants' responses to post-test SSQ [29]. Pre-test ratings showed that participants did not suffer or only slightly suffered from the different symptoms before the experimental condition (general discomfort: M=1.01, SD=0.12; headache: M=1.12, SD=0.33; eye strain: M=1.27, SD=0.45; nausea: M=1.04, SD=0.20). One-way ANOVA showed no significant differences in pre-test sickness ratings between the three groups.

4.4.3 Presence

To measure presence, we administered the Igroup Presence Questionnaire (IPQ) [30]. The IPQ (available at http://www.igroup.org/pq/ipq/index.php) is a self-report scale with 14 items, comprising a general item related to the sense of "being there", and three subscales that evaluate the following independent dimensions: spatial presence (5 items), involvement (4 items) and experienced realism (4 items). Each IPQ item can be rated on a 7-point scale, ranging from 0 to 6.

4.4.4 Usability

To measure usability of the locomotion techniques, we employed the well-known System Usability Scale (SUS) [31]. The scale includes 10 statements and participants were asked to rate level of agreement on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). Since its introduction, this scale has been considered unidimensional and different studies reported an overall SUS score in the 0–100 range. More recently, a factor analysis revealed that the scale has two subscales: learnability (items 4 and 10) and usability (the remaining 8 items) [32]. In this paper, we will thus analyze each subscale as well as the overall SUS score.

4.4.5 Comfort

To measure comfort, we adapted the Device Assessment Questionnaire (DAQ) [33]. The DAQ was designed to compare pointing devices for computers and includes 13 items concerning required force, smoothness, mental and physical effort, difficulty to be accurate, slowness, fatigue of different parts of the body, general comfort and overall ease of use [33]. Each DAQ item can be rated on a 5-point scale, ranging from 1 to 5. We adapted items 2, 5 and 6 to make them explicitly related to the travel task (smoothness of movements, difficulty to be accurate in movement, and

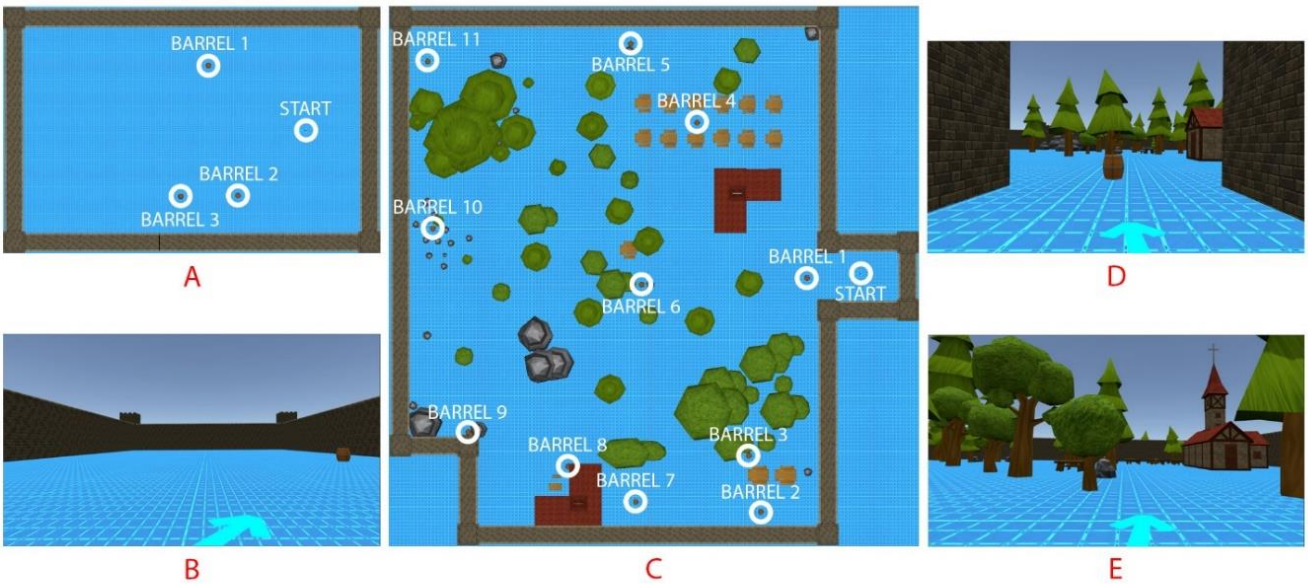


Fig. 2. The VEs used in the study: a) top isometric view of the tutorial VE, b) first-person perspective view of the tutorial VE as seen by participants at the beginning of the tutorial, c) top isometric view of the VE used for the assessment of performance, d) first-person perspective view of the VE for the assessment of performance as seen by participants at the beginning of the task, and e) first-person perspective view of the VE for the assessment of performance as seen by participants going towards "Barrel 4". White circles and labels in top isometric views indicate the start positions and the positions of the barrels that should be reached.

slowness in movement and rotation) and we added an item to measure spine fatigue, because leaning relied on movements that participants performed with their spine.

4.5 Procedure

We told participants that we were testing a technique to travel in a VE. We also informed them that in rare cases VR users could suffer from nausea or headache, and they could refrain from continuing the experiment at any time and for any reason. The experimenter also explained that he would ask them to fill some questionnaires in an anonymized form. After participants gave their consent, they filled an initial questionnaire concerning the information described in Section 4.3, and the questionnaire about sickness (pre-test).

Then, the experimenter invited participants to sit on a swivel chair, helped them to wear the HMD, and gave them the controllers. Since the controllers were shown in the VE, and their position and orientation were updated according to the movements of participants' hands, the experimenter gave them also to participants in the Leaning group even if leaning did not use the controllers to move. This was done to avoid any effect on presence that the absence of controllers could have caused. The experimenter explained how to move with the assigned locomotion technique in the tutorial VE. After participants tried the technique for 30 seconds, the experimenter invited them to move towards the barrel and told them that a new barrel was going to appear as soon as they reached one. The experimenter let participants practice with barrels in the tutorial for two minutes. Then, he told them that the next task consisted in using the same technique in a more complex VE. He explicitly told participants to reach the barrels as fast as possible. The experimenter started the VE for assessment and participants performed the task.

After the experimental condition, the experimenter helped participants remove the HMD and invited them to fill the questionnaires about sickness (post-test), presence, usability, and comfort.

5 Results

5.1 Performance

Time to complete the travel task (Fig. 3) was subjected to a between-subjects ANOVA. The analysis revealed a statistically significant difference, $F(2,72)=126.80$, $p<0.001$, $\eta_p^2=0.78$. Bonferroni pairwise comparison revealed that the differences between T group ($M=71.15$, $SD=23.78$) and J group ($M=165.42$, $SD=24.78$) as well as between T group and L group ($M=146.71$, $SD=17.15$) were statistically significant, $p<0.001$ for both. The difference between J group and L group was also significant, $p<0.05$.

5.2 Sickness

After calculating the changes in sickness symptoms by subtracting pre-test ratings from post-test ratings (Fig. 4), we analyzed the differences using Kruskal-Wallis test. The analysis did not reveal statistically significant differences in overall sickness, headache and eye strain. Differences in nausea were instead statistically significant, $X^2(2)=12.23$, $p<0.005$.

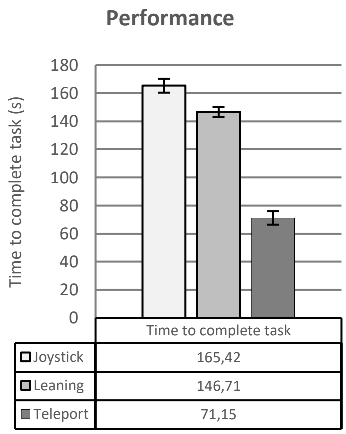


Fig. 3. Means of time to complete the travel task. Capped vertical bars indicate ± SE. Teleport was the fastest, and leaning was faster than joystick.

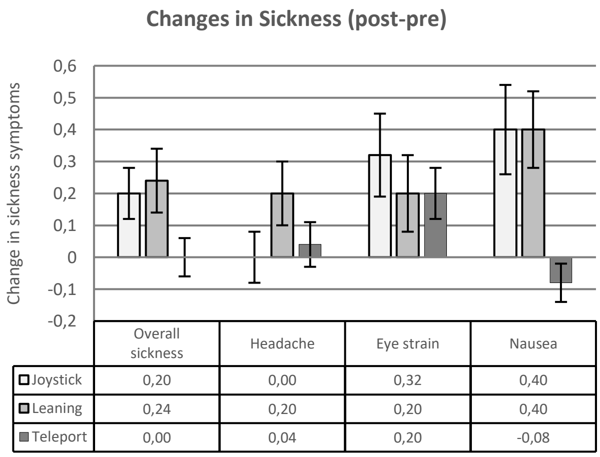


Fig. 4. Mean change in sickness symptoms. Capped vertical bars indicate ± SE. Positive values indicate an increase in sickness symptoms and negative value a decrease. Participants in the Teleport group experienced less nausea than participants in Joystick or Leaning groups.

Dunn-Bonferroni pairwise comparison revealed that the differences between T group ($M=-0.08$, $SD=0.28$) and J group ($M=0.40$, $SD=0.71$) as well as between T group and L group ($M=0.40$, $SD=0.58$) were statistically significant, $p<0.01$ for both. No significant difference in nausea was found between J group and L group.

5.3 Presence

Differences in presence (Fig. 5) were analyzed with a between-subjects ANOVA. No statistically significant differences were found for the IPQ total score, for the general item about the sense of "being there", and for the spatial, involvement and realism subscales of the IPQ.

5.4 Usability

SUS scores (Fig. 6) were submitted to a between-subjects ANOVA. The analysis revealed a statistically significant difference for the overall SUS, $F(2,72)=8.93$, $p<0.001$, $\eta_p^2=0.19$. Bonferroni pairwise comparison revealed that the difference between T group ($M=88.30$, $SD=9.15$) and L group ($M=74.90$, $SD=11.76$) was statistically significant, $p<0.001$. The difference between T group and J group

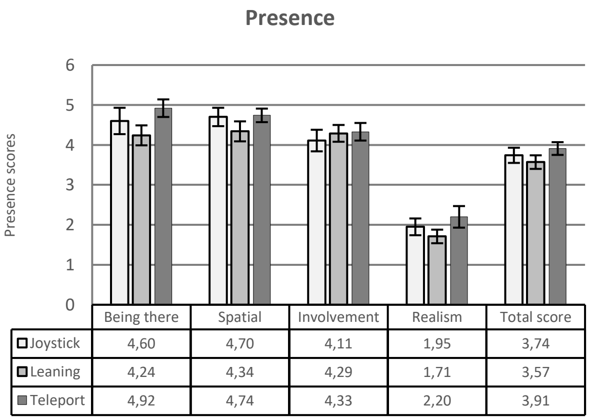


Fig. 5. Mean scores for presence and its subscales. Capped vertical bars indicate ± SE. No statistically significant differences between joystick, leaning, and teleport were found for presence.

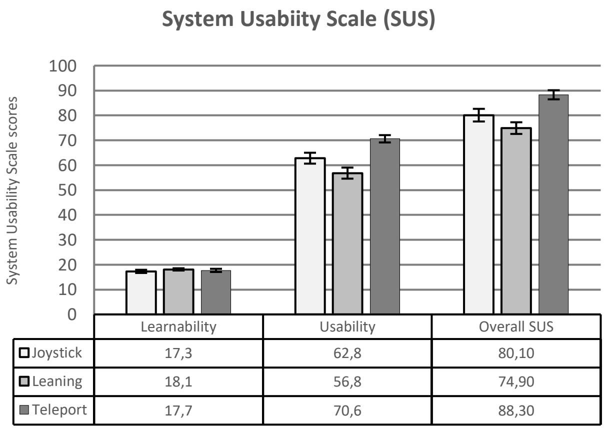


Fig. 6. Means of learnability, usability and overall SUS score. Capped vertical bars indicate ± SE. Teleport received a higher SUS score than joystick and leaning.

(M=80.10, SD=12.70) was also significant, $p<0.05$. The difference between J group and L group did not reach significance.

No statistically significant differences were found for the learnability subscale. The analysis revealed instead a statistically significant difference in the usability subscale, $F(2,72)=12.09$, $p<0.001$, $\eta_p^2=0.25$. Bonferroni pairwise comparison revealed that the difference between T group (M=70.60, SD=7.37) and L group (M=56.80, SD=11.08) was statistically significant, $p<0.001$. The difference between T group and J group (M=62.80, SD=10.95) was also significant, $p<0.05$. The difference between J group and L group did not reach significance.

5.5 Comfort

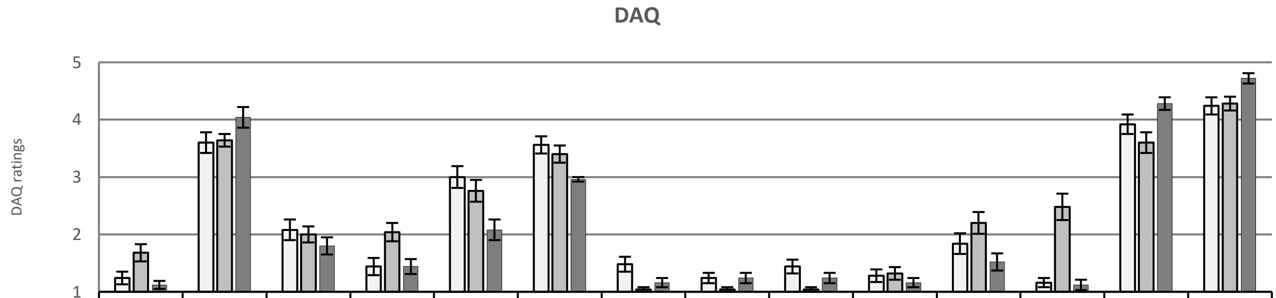
Differences in the ratings of each DAQ item (Fig. 7) were analyzed using Kruskal-Wallis test. The analysis revealed statistically significant differences for required force, $X^2(2)=13.12$, $p<0.005$, physical effort, $X^2(2)=11.69$, $p<0.005$, difficulty to be accurate in movements, $X^2(2)=10.98$, $p<0.005$, slowness in movement and rotation, $X^2(2)=11.90$, $p<0.005$, finger fatigue, $X^2(2)=10.74$, $p<0.005$, arm fatigue, $X^2(2)=9.32$, $p<0.01$, neck fatigue, $X^2(2)=7.33$, $p<0.05$, spine fatigue, $X^2(2)=33.45$, $p<0.001$, general comfort, $X^2(2)=8.10$, $p<0.05$, and overall ease of use $X^2(2)=8.59$, $p<0.05$. No statistically significant differences were found for smoothness of movement, mental effort, wrist fatigue, and shoulder fatigue. Dunn-Bonferroni pairwise comparison revealed as statistically significant the differences that we report in Table 2. The remaining differences did not reach significance.

6 Discussion

Results confirmed our hypothesis about performance. By using instantaneous instead of continuous movement, teleport allowed participants to complete the task in much less time than the other two groups. The advantage of teleport over leaning extends the results found in [11] and [23] that showed a better performance of teleport over walk-in-place and hand flapping, two in-place locomotion techniques that rely on body motion as leaning. Interestingly, the results in [11] and [23] were found only when there were no obstacles, while teleport was slower than joystick with obstacles. On the contrary, teleport was faster than joystick in our study with obstacles. Observing the VEs in [11] and [23], one can notice that all obstacles were tall identical columns placed on a dense and regular grid, while in our VE there was a variety of more scattered obstacles with different heights (e.g., tall trees and low

TABLE 2
DAQ: Statistically Significant Pairwise Comparisons

Item	Group	Group	p-value
Required force	J (M=1.24, SD=0.52)	L (M=1.68, SD=0.75)	p<0.05
Required force	L (M=1.68, SD=0.75)	T (M=1.12, SD=0.33)	p<0.005
Physical effort	J (M=1.44, SD=0.77)	L (M=2.04, SD=0.79)	p<0.01
Physical effort	L (M=2.04, SD=0.79)	T (M=1.44, SD=0.65)	p<0.05
Difficulty to be accurate in movements	J (M=3.00, SD=0.96)	T (M=2.08, SD=0.91)	p<0.005
Slowness in movement and rotation	J (M=3.56, SD=0.77)	T (M=2.96, SD=0.20)	p<0.005
Slowness in movement and rotation	L (M=3.40, SD=0.76)	T (M=2.96, SD=0.20)	p<0.05
Finger fatigue	J (M=1.48, SD=0.65)	L (M=1.04, SD=0.20)	p<0.005
Arm fatigue	J (M=1.44, SD=0.58)	L (M=1.04, SD=0.20)	p<0.01
Neck fatigue	L (M=2.20, SD=0.96)	T (M=1.52, SD=0.77)	p<0.05
Spine fatigue	J (M=1.16, SD=0.37)	L (M=2.48, SD=1.16)	p<0.001
Spine fatigue	L (M=2.48, SD=1.16)	T (M=1.12, SD=0.44)	p<0.001
General comfort	L (M=3.60, SD=0.91)	T (M=4.28, SD=0.54)	p<0.05
Overall ease of use	J (M=4.24, SD=0.72)	T (M=4.72, SD=0.46)	p<0.05
Overall ease of use	L (M=4.28, SD=0.61)	T (M=4.72, SD=0.46)	p<0.05



	Required force	Smoothness of movements	Mental effort	Physical effort	Difficulty to be accurate in movements	Slowness in movement and rotation	Finger fatigue	Wrist fatigue	Arm fatigue	Shoulder fatigue	Neck fatigue	Spine fatigue	General comfort	Overall ease of use
Joystick	1,24	3,60	2,08	1,44	3,00	3,56	1,48	1,24	1,44	1,28	1,84	1,16	3,92	4,24
Leaning	1,68	3,64	2,00	2,04	2,76	3,40	1,04	1,04	1,04	1,32	2,20	2,48	3,60	4,28
Teleport	1,12	4,04	1,80	1,44	2,08	2,96	1,16	1,24	1,24	1,16	1,52	1,12	4,28	4,72

Fig. 7. Means of the different items of DAQ. Capped vertical bars indicate ± SE. There was no item in which teleport obtained a statistically significant worse rating than the other techniques.

benches). The fact that the obstacles in our VE were more scattered, and some of them were so low that the teleport ray could pass over them, can partially explain the difference in the results, and suggests that teleport may lead to better performance in VEs with no obstacles or scattered and low obstacles, while joystick may lead to better performance in VEs with several, tall obstacles. Further studies with different kinds of VE structures are needed to explore this aspect more thoroughly. Notably, another element that can explain why teleport performance was better than joystick in our study is the presence of the arrows that supported wayfinding by pointing to the next barrel to reach, as shown in Fig. 2D and E. We used the arrows in all experimental conditions because we focused on travel and not on wayfinding, but teleport required more orientation time than continuous movement in [3], so the worse performance of teleport with respect to joystick in [11] and [23] can be due to orientation time. Further studies focusing on wayfinding are needed to assess if teleport might cause disorientation and possibly increase wayfinding time if no support is provided.

We found joystick to be slower than leaning. This extends the results found in [26], where head tilt was faster than joystick, and it is also aligned with the results of [12], where leaning was better than joystick in terms of error in degrees to turn towards a target. Studies that compared instead time to go through a sequence of waypoints with joystick and with two different techniques based on physical motion (walk-in-place [11], [23] and hand flapping [23]) found that joystick was faster. The different locomotion performance over joystick can be explained by the fact that walk-in-place and hand flapping require to continuously move respectively feet and hands to keep moving the viewpoint forward, while leaning requires just a little bending of the torso to move the viewpoint. Moreover, unlike walk-in-place and hand flapping, leaning has the advantage of allowing for multi-directional movement (i.e., it allows users to go backwards, move diagonally, and strafe in the VE without rotating), and this makes this technique similar to joystick, but without the need to interact with a controller. Further studies comparing walk-in-place and hand flapping with multi-directional and forward-only implementations of leaning and joystick could be useful to better understand how much the multi-directional movement impacts on performance.

Results confirmed our hypothesis that joystick causes more sickness than teleport. More precisely, it caused more nausea, while we did not find statistically significant differences between the groups for headache, eye strain, and overall sickness. Two previous studies that compared sickness with joystick and teleport [7], [10] found less ocular-motor symptoms [7] and less overall sickness [7], [10] with teleport, while other studies [11], [23] found no statistically significant differences by analyzing the average of the scores for the different symptoms. We instead found a statistically significant result concerning nausea. Nausea increased more in J group than T group probably because the head remained still with both techniques, but the eyes perceived a continuous movement with joystick, causing a sensory conflict between visual and vestibular systems [27]. The sensory conflict involved the ground, the walls, the trees and other elements of the VE that people normally consider stationary. The rest frame hypothesis [34] highlights how sickness can be caused by conflicting sensory cues concerning the rest frame, i.e., the part of the scene that is considered stationary. Moreover, since teleport allowed users to complete the task in much less time, participants in T group were also less exposed to VR, and it is known that the length of exposure is linked to ocular-motor symptoms [35]. This could also contribute to explain why teleport caused less nausea than leaning. It is important to note that all symptoms of sickness, including nausea, scored very low in our study, regardless of the employed technique (all the average ratings were between "none" and "slight"). However, while no participant reported any nausea with teleport, seven (respectively eight) participants reported slight nausea after using joystick (respectively leaning), and two (respectively one) reported moderate nausea. Interestingly, although leaning allowed users to move in the VE in the same direction of their heads, the hypothesized attenuation of the sensory conflict did not lead to any significant improvements in sickness with respect to joystick. Possibly, there was still a sensory conflict that caused nausea with leaning because the movement in the VE was larger than the physical movement of the head. In particular, when participants moved in the same direction in the VE for a long time, their head remained still at a distance from its resting position, while their eyes perceived a movement with respect to the resting frame. Previous studies that assessed sickness with leaning and joystick [8], [9], [26] did not find any statistically significant differences in this variable, and our study with a larger sample of participants found no significant differences between these two techniques as well.

Surprisingly, we did not find any statistically significant differences in the total presence score and its subscales. We expected that teleporting could break the sense of being in the VE more than a continuous movement that is more similar to the way people move in the real world, but this did not happen. In all groups, presence scores were high (between 4 and 5 in a 0 to 6 scale) for the sense of being there as well as for spatial presence and involvement subscales. Only realism scores were low in the three conditions, but this was probably due to the VE, which did not include realistic 3D models. Previous studies comparing joystick and teleport found no significant differences in presence [10], [11], an overall significant difference for presence that was not followed by pairwise comparisons analysis [23], or an higher presence with teleport than other techniques, but not than joystick [7]. Previous studies comparing presence with joystick and leaning [8], [9], [26] found no significant differences [8], [9], or higher presence with leaning [26]. Our study was the first to compare presence among all the three considered techniques together, and found no significant differences in presence, involving a larger sample of participants than previous studies.

SUS scores did not confirm our hypothesis about learnability, although the premises on which we based it did hold. More precisely, the initial questionnaire confirmed that participants were more familiar with joysticks (M=5.67, SD=1.66) than with systems that detect body movements (M=3.64, SD=1.67) for playing 3D videogames (paired samples t-test, $p<0.001$). Despite the higher familiarity with joysticks in 3D videogames and the lack of significant differences in familiarity between groups confirmed by ANOVA, there was no significant difference in learnability, which was high in all groups (above 17 in a 0 to 20 scale). Usability subscale and overall SUS were high in all groups as well, but the statistical analysis revealed that teleport was significantly more usable than each of the other techniques. In previous studies that compared some aspects of usability of teleport and joystick [11], [23], joystick received slightly better scores than teleport, but no pairwise comparisons were reported [23] or they did not reach significance [11]. Our study involved a larger sample of participants and used a well-known usability scale, finding that teleport was more usable than joystick, and such advantage of teleport was found also over leaning. We did not find instead significant differences in usability between leaning and joystick. A previous study that compared learnability of joystick and leaning [26] found no difference between the two techniques as well [26]. Interestingly, joystick was more usable than leaning in [8], easier to use than leaning in [9], and less difficult to understand than another technique based on physical motion (walk-in-place) in [11]. Although the differences were not significant in our study, the mean values we found for usability subscale and overall SUS are consistent with these results.

Results confirmed our hypotheses that leaning required more physical effort than each of the other techniques. Previous studies already showed that joystick and teleport required less effort than other techniques that rely on physical motion, such as walk-in-place [11] and hand flapping [23]. Although leaning requires only little bending of the torso instead of the continuous physical movements of walk-in-place and hand flapping, our study showed that it still required more effort than joystick and teleport. Leaning also caused more spine fatigue than the other two techniques, as expected. However, it is important to note that physical effort was considered low even with leaning, and spine fatigue was considered moderate to low. A significant difference was found also for required force. The mean score with leaning was the highest, but the means were very low in all conditions. Means were very low also for the other aspects of fatigue. For neck fatigue, the mean score with leaning was the highest, but the difference was significant only with respect to teleport. For finger and arm fatigue, highest mean scores were found with joystick, but the differences were significant only with respect to leaning. The lack of differences between joystick and teleport was probably due to the fact that both groups used the handheld controllers. No significant differences were found for wrist and shoulder fatigue. Moreover, we found no difference between the techniques in mental effort, which on average was low. Interestingly, being accurate in movements using joystick turned out to be more difficult than teleport, possibly because participants using teleport could see the halo indicating currently pointed position (Fig. 1B) and adjust the position before releasing the button to be teleported. No previous study compared joystick and teleport on this difficulty, but two studies found perceived precision of movement with joystick to be higher than leaning [8], [9], while we did not find significant differences on this aspect between the two techniques. Consistently with locomotion performance results, teleport obtained significantly lower scores for slowness than each of the other techniques. No significant difference was found for smoothness of movements, while general comfort was higher with teleport than leaning. The difference between leaning and joystick was not significant, but the means confirmed the trends found in [8] and [9]. Finally, consistently with SUS, the overall ease of use in DAQ was higher with teleport than with the other two techniques.

In summary, our study showed that teleport was better than the other two techniques in terms of time to complete the task, nausea, and usability. It was also better than leaning in terms of required force, physical effort, spine fatigue, neck fatigue, and general comfort. Finally, it was better than joystick in terms of difficulty to be accurate in movements. We expected teleport to be worse than the other techniques in terms of presence or learnability, but no significant differences were found. Moreover, there was no measure in which teleport obtained a statistically significant worse result than the other techniques. For these reasons, teleport could be recommended as appropriate for a wide range of VR experiences, such as those in which users need to travel fast without feeling sick or tired as well as those in which usability plays a fundamental role.

The differences between leaning and joystick were limited: leaning was better than joystick in terms of time to complete the task and in finger and arm fatigue, but worse in terms of required force, physical effort, and spine fatigue. Therefore, while several measures support the use of teleport in different VR experiences, the choice between leaning and joystick is subtle and more dependent on the specific context of use.

It is important to note that our results were found with young users, most of whom were familiar with videogames. Although the sample is likely representative of an important segment of users that will experience VR with consumer HMDs, the results cannot be generalized to other categories of users, e.g., older users and/or users who are less familiar with videogames. Another limitation of the study is that it involved a male-dominated sample, so further studies on a gender-balanced sample are needed.

7 Conclusion

In this paper, we studied the effects of joystick, teleport, and leaning techniques for locomotion in place using an HMD with 6-DOF tracking of user's head and handheld controllers. While previous studies compared a subset of these techniques with other techniques and usually involved small samples of users, our study is the first to thoroughly compare all three techniques together on a large sample (75 participants). Moreover, in addition to locomotion performance, commonly investigated in previous studies, we included measures of sickness, presence, usability, and comfort, that were considered less often, yet can play an important role in the way users experience VR. Analysis of the different variables found that teleport allows users to move faster, causes less nausea and is more usable than the other two techniques, while no significant differences were found for learnability and presence. Only small differences were found between the other two techniques. Results highlight the role of teleport as a valid solution for in-place locomotion.

The present study focused on travel. In future studies, we will concentrate on wayfinding, because teleport could be more disorienting than the techniques in which viewpoint movement is continuous [3]. This motivates further studies, with and without different wayfinding aids.

Moreover, the fact that some performance results of previous studies differed from ours when using a different type and arrangement of obstacles in the VE [11], [23], indicates the need for further studies. We will compare the techniques in VEs with obstacles of different types (tall vs. low, narrow vs. large) and VEs with different arrangements of the obstacles (regular grid vs. scattered positions, few vs. many obstacles), including VEs that are more complex than the one we used in our study.

A final aspect that would need further evaluation is how much the multi-directional movement of joystick and leaning affects their performance with respect to techniques that allow only for forward movement (e.g., walk-in-place). This could be done by evaluating multi-directional and forward-only implementations of joystick and leaning as well as different forward-only techniques.

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