A virtual reality perceptual study of multi-technique redirected walking method

Jesus Mayor, Laura Raya, Sofia Bayona, and Alberto Sanchez

***Abstract*—Within virtual reality experiences, locomotion methods manage the user's movement within the virtual environment. The use of natural locomotion, common in virtual reality, can be limited in video games with large scenarios. Thus, video games with gamepad or teleport-based locomotion methods are gaining importance. Redirected walking methods focus on maximizing the exploitation of the real workspace. As the user moves in the real environment, subtle modifications are applied to that movement within the virtual environment. Although the results of the Multi-Technique Redirected Walking (MTRW) method that combines the application of four gain algorithms are promising, a perceptual evaluation with users is needed to determine its suitability.**

This paper presents the perceptual evaluation of the presence and cybersickness factors for the MTRW method, comparing it with a Fully Natural Walking (FNW) method. The presence factor was measured with the Igroup Presence Questionnaire (IPQ), and no significant differences in the overall presence score were detected between the FNW and the MTRW methods. The cybersickness factor was measured using the Simulator Sickness Questionnaire (SSQ) and, this time, significant differences in cybersickness between the two locomotion methods were obtained. The potential increase in cybersickness should be weighed against the benefit of maximizing workspace utilization.

***Index Terms*—Virtual Environment Locomotion, Presence, Cybersickness, Player Satisfacion, and User tracking**

I. INTRODUCTION

VIRTUAL Reality (VR) technologies have shown great advances in recent years both at hardware and software levels. Specifically, locomotion methods that allow users to move within the virtual world are a current line of scientific interest, as they significantly influence the sensations of virtual reality users [1]. Some studies indicate that the more similar to real-life a virtual locomotion method is, the higher the user's perceptual rating becomes [1], [2], [3]. For example, in Fully Natural Walking (FNW) or real walking method [4], the user's virtual movements follow the same scale as the tracked physical movements. These movements can be used to move around the workspace or even to interact, however, it does not always go together. In this manuscript we will refer to the FNW method as a fully scaled method (for both interaction and locomotion).

FNW method produces great advantages, such as a greater sense of presence and low cybersickness [1]. However, users are limited to the physical workspace available in their environment or to the working dimensions of the hardware they are using. This can reduce user engagement in virtual reality experiencies with large scenarios.

To overcome the physical limitations of some room-scale locomotion methods, Redirected Walking (RW) methods emerged [5]. RW methods create the illusion of walking in a much larger virtual environment than the physical space a user is actually in. Subtle manipulations, ideally imperceptible to the user, are used to alter the perception of movement in VR and make the most of the physical space. Therefore, new RW methods have been a recurring research topic in recent years to achieve a larger virtual workspace without the knowledge of the user [6], [7].

The modifications used in the RW methods are performed by gain algorithms [8]. There are different types of gain algorithms: (I) which transform the movement into rotation (curvature gain) [5], (II) which scale the rotation into a different rotation (rotation gain) [9], (III) which scale the movement into a different one (translation gain) [10], or (IV) which transform the rotation into translation (deviation gain) [11].

In addition, there are different approaches to make effective the redirections applied to the user's motion: (I) if the motion redirection is to a specific area, the RW method is classified as *steer to orbit* [12]; (II) if the redirection is to the center of the workspace, the method is called *steer to center* (S2C) [12], and (III) if the redirection is to multiple centers of interest, it is named *steer to multiple targets* [13]. To achieve these subtle redirections, a correct definition of the gain algorithms [14] and the correct prediction of the user's direction is essential [15].

Currently, RW methods can get users to walk in a straight line within the virtual space without touching the walls of the physical space, but large workspaces with dimensions of, for example, $31m \times 31m$ are needed [16]. However, a workspace of these dimensions is not always available, and further research is needed for smaller workspaces.

In our previous work, a novel RW method called Multi-Technique Redirected Walking (MTRW) was presented and described in depth [11]. This method intelligently predicts the user's movement and proposes the union of four gain algorithms in order to make better use of the workspace (how these gain algorithms work will be briefly described in Section II-B). The results shown by this algorithm were positive, significantly reducing the physical space required to

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walk in a virtual straight line. However, that research did not focus on capturing the user's perceptual sensations that may be produced by this novel RW method and its four gain algorithms. Next we define the perceptions we evaluate in the current work:

- **Presence.** It is defined as a state of consciousness that indicates the psychological sensation of being within the virtual environment [17]. The presence feature is essential in the effectiveness of VR experiences allowing, for example, to use HMDs as an element of pain distraction [18]. However, it should be noted that presence is affected by the locomotion method used in the virtual experience. Some studies indicate that the more natural or closer the chosen method is to reality, the greater the presence can be [2], [1].
- **Cybersickness.** It is the effect that produces sensations similar to those perceived by motion sickness and can produce feelings of disorientation, nausea, vertigo, sweating, etc. Specifically, cybersickness is the result of a discrepancy between the visual simulation of the perceived motion and the sensation of motion received by our vestibular system, the system in charge of balance in our inner ear [19]. An inappropriate design decision in the method of locomotion through the virtual world can lead to unpleasant consequences for the user, such as dizziness or fatigue [20]. Hence, trying to reduce the sensation of cybersickness is another important milestone in the current state of the art [21].

Thus, this work designs a virtual experience to evaluate the factors of users' presence and cybersickness when applying the MRTW method.

The structure of this manuscript is as follows. Section II will present similar evaluation studies and define the methods involved in the present evaluation. In Section III we will define in detail the evaluation method used and the virtual experience developed. The final results of the experiment are presented in Section IV and discussed in Section V. Finally, we conclude in Section VI.

II. RELATED WORK

The present manuscript proposes to evaluate the MTRW method both in terms of the presence and cybersickness, with the objective of determining if its use in those terms is appropriate. While our previous work in [11] concludes that the method MTRW is efficient in terms of effective space, being able to virtually expand the workspace in relation to the existing one in the physical world, there is no formal evaluation of the perceptual implication of its implementation.

It is common to find studies in the state of the art that measure characteristics such as presence or cybersickness separately [21], [22], without taking into account that there is a possible influence between both factors [23]. Weech *et al.* [24] report several articles that relate the feeling of presence with cybersickness, concluding that there is an inverse relationship between both symptoms. For this reason, to carry out a complete study of the MTRW locomotion method [11], we consider that it is necessary to evaluate both factors together.

Research on the suitability of different existing locomotion methods is a frequent topic in the state of the art [1]. The research of Zielasko *et al.* [25] measures various types of hands-free locomotion methods (the Walking-in-place method or the Shake-your-head method) for data visualization within a virtual environment. In it, several methods are analyzed, detecting which of them is best for data visualization by measuring presence and cybersickness.

Another example that analyzes methods with room-scale is the study developed by Langbehn *et al.* [26]. This study analyzes the Teleport, RW, and Human Joystick methods. Among these three methods, the authors conclude that the RW method provides better spatial recognition than the other two. On the other hand, they indicated that the so-called human joystick method is the method that produces the greatest cybersickness of the three. However, in their study, they leave aside the widely used methods, such as the Gamepad method or the FNW method [26].

Recent studies indicate that the FNW method is one of the best-rated methods in terms of presence and cybersickness [1]. For this reason, we present in this manuscript a comparative evaluation of the MTRW method with FNW, which is considered the gold standard method for these factors. Both methods, MTRW and FNW, are defined next.

A. Fully Natural Walking

The FNW method for the user is the closest method to reality since it uses the 6 degrees of freedom (6DOF) of movement of the Head Mounted Display (HMD) to move naturally through the virtual environment [27], [28]. The user's movement through the virtual environment is performed as the user moves through the real environment, avoiding sensory dissonance between the physical and the virtual movements [20]. Displacement position mapping allows any movement made by the user in the real world to be translated to the same movement in the virtual world.

To foster users' confidence within the virtual workspace, it is common to display the boundaries of the physical space within the virtual space in an explicit manner. Thus, it is common to represent the boundaries of the physical workspace with thin lines of striking color, trying not to overly disturb the realism of the virtual space displayed.

With this method, the interaction with the virtual objects is usually done via the absolute positioning VR controllers, using the 6DOFs. Generally, to interact with an object, users will approach the controllers to touch it, grasping it by pressing one of the buttons. Then, with the natural movement of the hand, the subject will be able to manipulate the object by rotating and moving it in 6DOF. However, as discussed above, since FNW method is limited to the workspace available to the user to either interact or move around.

B. Multi-technique Redirected Walking

As noted above, MTRW [11] is a method of RW that attempts to overcome the spatial limitations found in the FNW method. This method applies subtle modifications of the movement in the virtual world with respect to the natural locomotion

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performed by the user. In order to optimize space versus other locomotion methods, the MTRW method includes four gain algorithms. Each of these gain algorithms is responsible for jointly making maximum use of the workspace by altering the user's perception of movement in the virtual world, applying subtle modifications to the user's physical movements. The strategy followed in all four gain algorithms is multiscaling, meaning that the scale of these modifications varies over time [29]. Moreover, this scaling is automatic, following heuristics such as the proximity to workspace boundaries or the motion prediction. These algorithms are briefly described below (see [11] for a deeper understanding).

- **Curvature gain**. This technique takes advantage of the user's physical displacement to subtly apply virtual rotations, causing a curve in the virtual space in which the user is located. This subtle rotation is proportional to the displacement made by the user, being partially or totally masked by it. In this way, the technique avoids the workspace boundaries and increases the virtual space that is traveled before reaching those boundaries.
  In the case of MTRW, depending on the user's motion prediction, the virtual rotation is applied up to a maximum of the user's perceptual threshold. In addition to this automatic scaling of the virtual rotation, a rotation proportional to the displacement made by the user is applied.
- **Rotation gain**. In MTRW algorithm takes advantage of the user's physical rotations, increasing or decreasing the effect of the virtual rotations. Unlike curvature gain, this type of technique is applied both when users are in motion and when users are standing still and turning their heads. The decision to apply more or less scaling of the rotations depends on the user's displacement prediction whether the user is oriented to the center of the workspace or not. In the state of the art, Bruder *et al.* [30] analyzed the limits to which such gains in rotations can be scaled. Schmitz *et al.* [31] redefine such perceptual limits by indicating that the presence decreases if the user perceives the rotation gain. Furthermore, Sun *et al.* [32] applied rotations taking advantage of instants of eye movement to explore the environment. This technique has shown promising results, despite requiring eye-tracking inside the VR headset. Although this gain algorithm has favorable perceptual results, significant differences in spatial recognition have been reported in some cases [9].
- **Traslation gain**. This algorithm consists of scaling the translation performed by the user in physical space. Taking advantage of the user's motion a gentle and proportional virtual displacement is applied covering a larger virtual space. Wilson *et al.* [10] evaluate what extent the translation gain can affect the efficiency of task performance. To do so, they approached the scaling coefficients consistently throughout the course of each of their studies, reporting that those studies with higher scaling coefficients had a negative effect on task performance.
  In contrast, some studies analyze the time-varying scaling [33]. They found that users are susceptible to abrupt changes in translation scaling, and it is necessary to be subtle in the variation. This scaling of the virtual translation can also lead to modifications of the biomechanics of the gait cycle [34]. In MTRW we can also find a scaling of the variable displacement. But this scaling varies continuously and progressively over time, so there should be no abrupt changes in the scaling.
- **Deviation gain**. This algorithm was introduced for the first time in [11]. The main idea behind the deviation gain algorithm is to transform physical rotations into virtual translations. As explained in the original paper, the deviation gain follows the following equations:

  $$\lambda_t = \cos(\angle(\vec{f_t}, \vec{s_t})),$$

  $$DG_{t+1} = \frac{\vec{s_t}}{||\vec{s_t}||} \cdot \frac{|r_t|}{D_c} \cdot |\lambda_t|.$$

  The resulting deviation gain $DG_{t+1} \in \mathbf{R^2}$ is measured in m/rad units and it defines a rotation necessary to move a specific distance. It is calculated using a configurable deviation constant $D_c \in \mathbf{R}$ that transforms the real rotation $r_t \in \mathbf{R}$ into virtual displacement. To attenuate cybersickness, the smoothing factor λ_t uses the forward or facing vector $\vec{f_t} \in \mathbf{R^2}$ to reduce the effect of the deviation gain when the prediction of the user displacement $\vec{s_t} \in \mathbf{R^2}$ does not follow the same direction. Because the result of dividing the rotation $(|r_t|)$ by the rotation constant (D_c) is a scalar value and we need to apply the deviation gain in a specific direction, it is worth noting the use of $\vec{s_t}$ as the direction of application of this algorithm, which uses the normalized prediction vector $(\frac{\vec{s_t}}{||\vec{s_t}||})$ to direct the new translation gain. For a better understanding of this algorithm, for large values of D_c, the effect is decreased; smaller values achieve a higher translation.
  Unlike the curvature or translation gain techniques, this algorithm can also take effect if the user is standing still and observing his/her surroundings. This is possible thanks to the user's displacement prediction over time.

As MTRW uses automatic scaling in those gain algorithms, the user's perception thresholds must be previously calibrated. The MTRW method also has a calibration system to provide each user his/her non-perceptible level of application for each algorithm. This calibration is performed prior to the use of the method so that it can be applied in a way that is adapted to each user.

In the state of the art, it is possible to find studies that combine the application of several of the gain algorithms explained above to obtain a better utilization of the workspace. For example, it is possible to find research that combines rotation gain with curvature gain [35] or translation gain together with curvature gain [36] by calculating the maximum application thresholds of both methods. In fact, it is possible to find articles that combine up to 3 methods [37]. However, MTRW combines all four of the above algorithms at once to further exploit the workspace, but this could lead to greater effects on the presence or cybersickness.

III. EXPERIMENT

We propose to compare the MTRW method with the FNW method, to understand how the applied redirections affect the user in terms of presence and cybersickness, as well as to analyze the virtual workspace available in each case.

A. *Experimental environment*

For the present experiment, we intend to use a complete virtual experience to serve as a practical research element. Our virtual game has been developed with the Unity 2019.3.0f5 graphics engine for the HTC Vive HMD. This device offers high resolution (1080 × 1200 per eye resolution, FOV-110 degrees), good performance (90-Hz), and absolute positioning.

A virtual experience with a high level of presence was essential for our objectives in [1]. To ensure this level of presence in this case, we adapt the virtual experience shown in [1].

Originally, the virtual experience in [1] was composed of four parts. Each part evaluated variations of the presence depending on a different locomotion method. We tailored the experience by restructuring it into two parts, oriented to evaluate the two different locomotion methods (the new MTRW and FNW, balancing the order between the methods), and we added the neccessary modifications, such as expanding the virtual workspace needed to perform the tasks.

The following is a description of the content of the virtual experience:

- **First Part.** The storyline of the virtual game is introduced through a narrative that brings the user into a futuristic context.
  In this part of the test, the user is given time to explore the virtual environment. The narrative of the experience focuses on introducing the virtual characters by creating a funny atmosphere through a set of jokes and visual effects. The main goal is that the user creates a bond of empathy with the main character, a robotic cockroach, through interaction.
  After a narrative that allows the user to acquire a greater degree of trust with the avatar and to be able to experience in first person how the avatar is attracted by another of the avatars of the experience (Figure 1-Left), an event meant to unsettle the subject within the experiment occurs. The main avatar is hit by a metal box and a major malfunction results. The second avatar asks the user to help her immediately.
  This part of the narrative is intended to provoke feelings in the user, which will eventually be overcomed if the user performs the necessary and indicated interactions.
- **Second part.** The narrative leads the user to continue cooperating with the main avatar, further tightening the relationship with him. In this case, the avatar asks the user for help again, but through an ingenious task. This task consists of performing a simple visual puzzle in which two pieces in a broken machine must fit together.
  In this case, the task is fun and is made humorous through the narrative. After the machine is fixed, it is turned on, opening up a deep pit (see Figure 1-Center).
  After showing the user the depth of the pit, the user is asked to throw some suitcases into the pit to see that the portal is working properly. In this way, the user is given some time to calm down and gain confidence. After this, the user is asked to jump into the pit, which seeks to produce in the user the fear of jumping into the void. Upon jumping, the user is surprised with the destination of the portal (see Figure 1-Right). This leap of faith heeds to the idea proposed by Matthias and Beckhaus [38] of eliciting the sensation of magic in VR. Their research proposes performing tasks that cannot normally be done in real life to foster presence.

In this virtual experience, positional audio was used for the environmental sounds and the voices of the characters, as well as non-positional sound for the narrator, since the narrator is omnipresent [39]. Both parts were tested with both locomotion methods, balancing for the different subjects in the order the methods were presented. The entire experience of the experiment was displayed in order to ensure the correct development of the story.

Note HTC Vive's physical workspace is limited to $4m \times 4m$. Since both methods must allow traversing a virtual workspace larger than the available physical space, we implemented a reorientation technique to make it possible. Reorientation techniques are those that reoriente the user upon reaching the limits of the workspace, either automatically or by having to perform some conscious action on the part of the user for the reorientation [40]. These reorientation techniques are widely used in the FNW method and in the various RW methods when they can no longer optimize the virtual space, repositioning the user's virtual environment in another available direction so that subjects can continue their way.

Specifically, in our experiment, we have frozen the virtual environment and performed a fade to black, as this is the most common technique to reorient the user when the user reaches the limits of the workspace. At that point, users can change their real orientation (e.g., by turning 180 degrees) while the virtual orientation is fixed. Once the experience is reestablished, users can continue their path within the virtual environment [40].

B. *Method*

There are different methods to measure in virtual worlds the degree of sensation of presence or cybersickness [41], being the post-exposure questionnaire among the most accepted methods. Next, we described the questionnaires used.

1) Igroup Presence Questionnaire: A widely adopted mean of assessing presence is the Igroup Presence Questionnaire (IPQ) [42]. This questionnaire consists of three groups of questions and one general (G) question. These three groups were recognized as the *presence factors* for this questionnaire and were consequently measured separately through their specific questions:

- **Spatial Presence (SP).** This group of items addresses the feeling of being physically present in the virtual environment. It is the feeling of "being there", inside the virtual environment.

Figure 1. Screenshots of the virtual environment used for experimentation. The images shown are captures of the real-time gameplay.

- **Involvement (INV).** This group refers to the attention paid to the virtual environment and the perception of feeling involved in it.
- **Realism (REAL).** This group is related to the subjective user-experienced measure of the realism of the virtual environment.

The 14 questions associated with the IPQ are based on a psychometric Likert scale of 0 to 6 points to be answered by the users after their exposure to the virtual world. It is not necessary to complete this questionnaire prior to exposure since all questions refer to the experienced environment. According to the authors, the total calculation should be made through the arithmetic mean of each group, taking into account the previous inversion of these three questions. The general question (G) responds to an overall mean value of presence.

2) Simulator Sickness Questionnaire (SSQ): One of the most prevalent cybersickness questionnaires is the Simulator Sickness Questionnaire (SSQ) [43]. The questionnaire has 16 questions, which use a 4-point Likert scale where 0 means “Not at all” and 3 means “Severe”. These 16 questions are selected to report a null value in case the subjects are healthy and in a normal state.

This questionnaire consists of three sets of questions:

- **Nausea (N).** Stomach discomfort or stomach reactions.
- **Oculomotor (O).** Symptoms related to ocular problems.
- **Disorientation (D).** Sensations of loss of or related to loss of orientation.

To calculate the scores in these three groups of questions, it is necessary to apply certain weights. This is because not all symptoms analyzed are equally characteristic of cybersickness, so the results must be re-scaled to obtain similar measures for the three groups (N, O, D). Similarly, to calculate a total score on the SSQ (TS), it is necessary to apply an equation that weighs its final result [44].

C. Participants and procedures

The present experiment was conducted with 32 participants, of which 17 were male and 15 female, with a median age of 20 years (the range was from 18 to 48 years old, the mean was 22.75 and the standard deviation was 7.47). The perceptual threshold applied for each user is obtained from each user’s personalized calibration phase [11].

To carry out the experiment, the same conditions were maintained for all subjects in terms of procedure, I/O devices used, computer, and supervising person. The experimental conditions and procedures were ethically approved by the U-tad Ethics Committee, with the necessary consent of the users. To provide the same instructions to all users, these were read to avoid any variations. Participants were told to say in a loud voice any discomfort or adverse effects they may feel and they were informed they could decide to stop the experiments at any moment. The order in which the two parts of the experiment were presented was always the same, but the locomotion methods used were applied in a balanced manner. To minimize the effects of the order of presentation of the methods, each participant was presented with the locomotion methods in reverse order of the previous participant. Dividing the experiment into two parts also prevents long exposure to VR from being a factor to be taken into account for cybersickness in the case of finding significant differences [45].

The mean duration within the virtual world in both parts of the experience was 412.12 seconds (with a standard deviation of 43.26 seconds), having to travel a mean distance in the virtual environment of 60.61 meters (with a standard deviation of 18.96 meters) per experiment part and needing to perform total rotations of $10682° \pm 3564°$ in both directions (to the right and to the left).

After completion of each of the two parts of the experiment, subjects were asked to fill out a subjective questionnaire to assess presence (IPQ) and cybersickness (SSQ). The pause between each part to complete the post-exposure questionnaire was also used for the subjects to rest from the virtual environment between the two parts. The total duration of the experiences was approximately 30 minutes per subject, resting between all parts (calibration, first method, and second method) for 15 minutes and allowing the questionnaires to be completed in that time.

For a fair comparison, it was important to balance the order of appearance of the methods for each user, in order to analyze the variation between them. Nevertheless, it must be noted that, despite the breaks between exposures, users might not have been starting from a zero level of cybersickness at each exposure.

IV. RESULTS

In this section, we explain the results obtained in the experiments in detail. SPSS v24 was used for the statistical analysis and the creation of box plots.

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A. Analysis of the two parts of the experiment

Prior to the analysis of the results of the participants' sensations depending on the locomotion method used, we performed an analysis between the two parts of the virtual experience, checking whether the narrative content of the parts could provide significant differences for the variables under study (presence and cybersickness). In this way, we ruled out the possible influence derived from the content of both parts, avoiding influencing the subsequent analysis between FNW and MTRW locomotion methods. Table I shows the results obtained for the presence variables in the IPQ (G (general), SP (spatial presence), INV (involvement), and REAL (realism)) and cybersickness in the SSQ (TS (total score), N (nausea), O (oculomotor) and D (disorientation)).

Table I
GENERAL RESULTS OF THE PRELIMINARY ANALYSIS OF THE EXPERIMENT DEVELOPED.

	Variable	Mean	Std. dev.
IPQ	G	4.70	1.14
	SP	4.49	0.852
	INV	3.88	0.809
	REAL	2.99	0.927
SSQ	TS	28.81	28.90
	N	19.68	25.88
	O	18.71	20.83
	D	44.15	40.42
Movement metrics	Displacement	0.144 m/s	0.054
	Rotation	0.190 º/s	0.079
	Limits reached	6.14	3.280

Results (mean values) obtained in the preliminary analysis for the IPQ and SSQ questionnaires for the entire virtual experience.

The results obtained, 4.7 out of 6, regarding the general presence (G) for this sample, were higher than the mid-point value (see Table I) throughout the whole experience.

The data collected from the questionnaires completed by the participants of this experiment have been analyzed using a Shapiro-Wilk normality test. This test indicated that some of the variables under study followed a normal distribution, while others did not. Table II shows the results of this normality test analyzed at a significance level of $p < 0.05$.

Thus, some of the variables had to be analyzed with non-parametric hypothesis tests (such as the Wilcoxon test) and others with parametric tests (such as the Student's T-test). Table III shows both tests performed comparing both parts to identify if there are significant differences between them.

As we can see, IPQ did show differences for the subfactors of *involvement* (INV, $p = 0.006$) and *realism* (REAL, $p = 0.014$). However, the overall IPQ (G, $p = 0.694$) and the overall SSQ (TS, $p = 0.628$), showed no significant differences between the two parts. Therefore, since in the analysis of the overall variables both parts did not show significant differences, we assume that the content of each adapted part for the experiment does not significantly affect presence or cybersickness. Thus, we proceed to detail a comparative analysis between the two locomotion methods, taking into account presence, cybersickness, and virtual displacement metrics.

Table II
RESULTS OF THE SHAPIRO-WILK NORMALITY TEST OF THE PERCEPTUAL EXPERIMENT.

	Variable	p-value
IPQ	G	< 0.001 **
	SP	0.041 *
	INV	0.508
	REAL	0.191
SSQ	TS	< 0.001 **
	N	< 0.001 **
	O	< 0.001 **
	D	< 0.001 **
Movement metrics	Displacement	0.002 **
	Rotation	0.411
	Limits reached	0.001 **

The test performed analyzes the correspondence of the sample to a normal distribution, with the null hypothesis being that the variable analyzed corresponds to a normal distribution. Therefore, significant results ($p > 0.05$) will indicate that the sample does not follow a normal distribution (where: * = $p < 0.05$ and ** = $p < 0.01$).

Table III
TEST FOR SIGNIFICANT DIFFERENCES BETWEEN PARTS PERFORMED WITH WILCOXON AND STUDENT'S T-TEST.

	Variable	p-value	Part1	Part2
IPQ	G	0.694	4.69 ± 1.23	4.72 ± 1.05
	SP	0.656	4.43 ± 0.912	$4.55 \pm 0, 800$
	INV	0.006 **	3.67 ± 0.776	4.093 ± 0.797
	REAL	0.014 *	$2.83 \pm .892$	3.14 ± 0.950
SSQ	TS	0.628	15.98 ± 15.13	16.89 ± 16.02
	N	0.665	18.48 ± 23.85	20.87 ± 28.09
	O	0.293	19.90 ± 21.07	17.53 ± 20.86
	D	0.827	42.63 ± 39.99	45.68 ± 41.42

In white, we can observe the results obtained with the Wilcoxon test. In gray, we can observe the results performed with the Student's T-test (being: * = $p < 0.05$ and ** = $p < 0.01$).

B. Analysis between FNW and Multique Tecnique Redirected Walking

The objective of this research is to analyze the behavior of the MTRW method; for that, we compare it with the most widely used natural locomotion method which has the best perceptual ratings, the FNW method. Therefore, a statistical study was carried out to determine whether there were significant differences between the different analyzed locomotion methods. For this purpose, a Wilcoxon signed-rank test for the non-parametric variables and a Student's T-test for the parametric variables (both at a significance level of $p < 0.05$) were performed, as we did when comparing the two parts of the experiment. Table IV shows the mean results obtained, as well as the results of the significance tests for the different IPQ and SSQ variables.

1) Evaluation of presence: Specifically, in the case of the IPQ, no significant differences were detected for any of the variables associated with this questionnaire when measuring the subjective presence of the users. The mean results obtained for the IPQ variables were: "General" (G) ($p = 0.087$), "Spatial Presence" (SP) ($p = 0.237$), "Involvement" (INV) ($p = 0.564$) and "Realism" (REAL) ($p = 0.590$). As can

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Table IV
PRESENCE AND CYBERSICKNESS RESULTS OBTAINED FOR FNW AND MTRW.

	Var.	FNW	MTRW	p-value
IPQ	G	4.84 ± 1.08	4.56 ± 1.19	0.087
	SP	4.58 ± 0.838	4.41 ± 0.871	0.237
	INV	3.93 ± 0.818	3.84 ± 0.809	0.564
	REAL	2.95 ± 0.725	3.02 ± 1.10	0.590
SSQ	TS	22.91 ± 22.11	34.71 ± 33.71	0.015 *
	N	14.91 ± 16.24	24.45 ± 32.41	0.033 *
	O	13.98 ± 16.57	23.45 ± 23.69	0.008 **
	D	37.85 ± 35.57	50.46 ± 44.41	0.098

This table shows both means and standard deviations of both questionnaires for both locomotion methods. Also, it is shown whether the differences are significant through the Wilcoxon and Student's T-test statistics (where: * = $p < 0.05$ and ** = $p < 0.01$; FNW = Fully Natural Walking, MTRW = Multi-Technique Redirected Walking)

be seen, using a significance level of ($p < 0.05$) it cannot be stated that the differences found between the MTRW and FNW method are significant. The results are graphically represented in Figure 2.

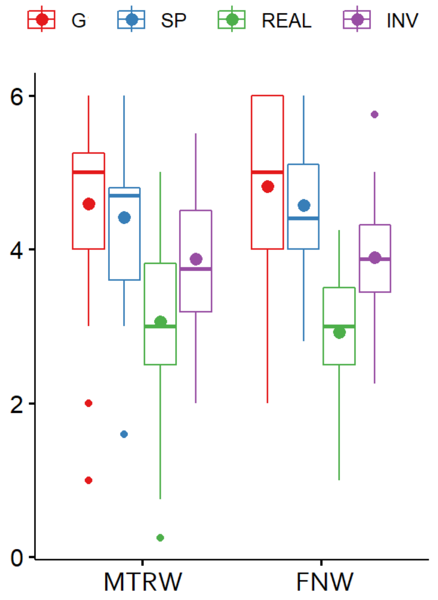

Figure 2. Results of the Igroup Presence Questionnaire: Comparison of FNW (Fully Natural Walking) with MTRW (Multi-Technique Redirected Walking). The score obtained for both methods is shown on the vertical axis. On the horizontal axis the different variables for both methods are shown. Outliers are represented by circles.

2) Evaluation of cybersickness: In the case of cybersickness analyzed through the SSQ subjective questionnaire, as shown in Table IV, statistically significant differences were detected for the variables: "Total Score" (TS) ($p = 0.015$), "Nausea" (N) ($p = 0.033$), and "Oculomotor" (O) ($p = 0.008$). However, no significant differences were shown for "Disorientation" (D) ($p = 0.098$) at a significance level of ($p < 0.05$). These results were obtained using a Wilcoxon test, generally indicating that FNW shows significant differences from MTRW when assessing cybersickness.

Figure 3 shows graphically the differences found between FNW and the MTRW method for measuring cybersickness.

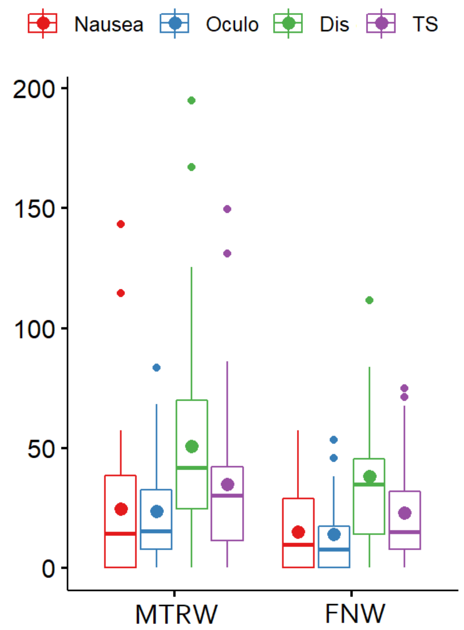

Figure 3. SSQ results: Comparison of FNW (Fully Natural Walking) with MTRW (Multi-Technique Redirected Walking). The cybersickness score obtained for both methods is shown on the vertical axis. On the horizontal axis the SSQ variables are shown, so that the comparison between the two methods can be appreciated. Outliers are represented by circles.

3) Evaluation of workspace utilization: The Shapiro Wilk normality test was shown in Table II in which, we can observe that the distance traveled ($p = 0.002$) and the number of times the limits were reached ($p = 0.001$), do not follow a normal distribution, so non-parametric tests should be used. On the contrary, the rotations performed during the experience showed to follow a normal distribution ($p = 0.411$), and parametric statistics should be used. Thus, as in the presence study, the different variables were analyzed by combining the use of Wilcoxon signed-rank tests and Student's T-test.

Table V shows the results obtained for both methods, as well as the significance tests indicating whether or not the differences are significant (at a level of $p < 0.05$). As we can see, no significant differences were found in either the distance traveled per second or the rotations performed per second during the experience. This could be because the user is not in constant motion during the experience, and there are large periods of time in which the user does not rotate or move. For this reason, the physical effort with respect to the time spent is reduced, not showing these differences in a noticeable way.

Therefore, no differences were found in the actual movement performed, which could indicate a similar effort on the part of the users per second for both methods.

On the other hand, we have detected a better use of the workspace through the significant differences found in the number of times the limits of the workspace were reached. These differences were produced thanks to the modifications applied in motion (with a mean of 0.092 m/s and a standard deviation of 0.057 m/s) and rotation (with a mean of $6.78°/s$ and a standard deviation of $3.95°/s$).

Table V
TEST OF SIGNIFICANT DIFFERENCES BETWEEN EACH METHOD PERFORMED WITH WILCOXON AND STUDENT'S T-TEST.

	FNW	**MTRW**	**p-value**
Real displace.	0.150 ± 0.061 m/s	0.138 ± 0.046 m/s	0.155
Real rotation	35.28 ± 9.22 °/s	34.87 ± 9.04 °/s	0.744
Limits reached	6.88 ± 3.04	5.25 ± 3.04	0.044 *

In white, we can observe the results performed with the Wilcoxon test, which showed significant differences for the number of times the limits were reached. In gray, we can observe the result performed with Student's T-test, which did not show significant differences (where * = $p < 0.05$ and ** = $p < 0.01$; FNW = Fully Natural Walking, MTRW = Multi-Technique Redirected Walking).

V. DISCUSSION

Next, we discuss the different results.

First, no significant differences were found in the distance traveled or in the rotations performed per second during the experience. These results are different from those obtained in the original investigation [11]. This could be due to the fact that in such a commercial experience, users do not walk as much on average as they might in a walking experiment.

However, while the present results did not show significant differences, MTRW continues to reduce the number of times that reorientation techniques need to be used when reaching the limits. This is positive since the use of MTRW is explicit to the user and can be easily used in commercial experiences.

Second, despite the significant improvement in workspace utilization, we could not find significant differences regarding the user's level of presence in the sample. This does not imply that both methods are equivalent, but it is certainly a promising result because, if further analysis would support our results, it could be it might be interesting to study the possibility of substituting FNW for MTRW, in conditions where the virtual workspace needs to be larger than the physical workspace. This would represent a promising alternative for video games with wide, large-scale, and open-world scenarios.

Third, in the data obtained after our experiment, significant differences have been detected regarding cybersickness when using the MTRW method. These results, although undesirable, were to be expected since the method induces modifications in the user's movement that are not present in the FNW method.

The effect of cybersickness could be individually minimized by the calibration phase. However, when instructing the user to report when he/she gets dizzy in order to optimize and customize the calibration, the possible influence on the user's suggestibility should be considered [46].

The calibration system asks the subject to indicate the moment at which they begin to detect the subtle modifications, as detailed in [11]. Therefore, the parameterization values of the gain algorithms are obtained from the moment immediately preceding the subject's indication. This could lead to two drawbacks: (I) that the previous value obtained in the calibration method is not adequate and it may be interesting to use the average of the perceptual limits obtained between subjets instead of the upper non-noticeable limit, and (II) that indicating to subjects that they may notice displacement discrepancies during the calibration increases subjects' awareness of these discrepancies [46]. In both cases, it may be necessary to adapt the calibration system before the algorithm, but it should not entail to modify the MTRW method as such.

Furthermore, it should be kept in mind that cybersickness is a very complex phenomenon and that its evolution is not predictable [47]. In this regard, it is important to note that our study did not incorporate a full day of rest between the different exposures, which does not eliminate the possibility that, although our participants did not express discomfort or ask to pause the experiment, there could be a carry-over effect between the different parts of the experiment.

VI. CONCLUSIONS

In the present research, the MTRW locomotion method is compared to the FNW locomotion method. The advantages in terms of presence and cybersickness offered by the FNW locomotion method are limited by its workspace constraint. A RW method that offers similar perceptual sensations in terms of cybersickness and presence - but allows the virtual workspace to be expanded - could be more suitable for large virtual environments.

Specifically, a study has been conducted evaluating the use of workspace by both locomotion methods, as well as two perceptual factors: presence and cybersickness.

In the study carried out, MTRW did not show significant differences in the presence perceptual sensation compared to the FNW method. Presence was measured through the IPQ questionnaire in a sample of 32 participants. Thus, under the conditions of this study, we found no significant differences in the feeling of presence between the two methods. However, further experiments are needed to determine whether this is still the case under all conditions.

In terms of space utilization, the workspace provided by the HTC Vive HMD ($4m \times 4m$) was not large enough to never reach the workspace limits with both methods during the experiment. Therefore, we designed the experiment to evaluate how many times a user reaches these space limits with each method. Based on the results obtained, better workspace utilization was obtained with the MTRW method, according to the significant differences found in the number of times the workspace limits were reached.

Significant differences in cybersickness levels have been detected, reporting less cybersikness when using the FNW method. Hence, it remains to be studied how to further improve the calibration or the MTRW method. Likewise, a generally high level of cybersickness has been detected for both methods. We think it could be due to the previous calibration phase, where users must indicate when they detect discomfort for each of the four algorithms. This could influence users' suggestibility or predisposition to feel it [46]. Hence, we plan to improve the calibration of the MTRW method in future work.

We recommend for future studies to let participants rest one day between different exposures to avoid the carry-over effect. Another improvement would be to take into account the measurement of possible delayed onsets in cybersickness.

In conclusion, MTRW is a method that helps to optimize the workspace and shows no significant differences in presence under the conditions of our study with respect to the FNW method. In this way, MTRW is presented as a useful method when a virtual space larger than the available workspace is needed. It appears to maintain the high presence levels provided by FNW though increasing cybersickness. This potential increase in cybersickness should be weighed against the benefit of maximizing workspace utilization. However, to avoid the calibration phase issues, further studies with the previously obtained perceptual thresholds should be carried out to improve workspace utilization while mitigating cybersickness.

In future studies, we plan to extend this comparative study to other widely used methods such as Teleport or Gamepad. In addition, it would be very interesting to determine the minimum required workspace so that the use of this method not only reduces the number of times users reach the limits of the workspace but also ensures that users never reach those limits.

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