



A novel low cybersickness dynamic rotation gain enhancer based on spatial position and orientation in virtual environments

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Abstract

Hardware and software resources nowadays make possible new Virtual Reality (VR) interaction methods. Numerous challenges have been involved over the years, and one of the most interesting is locomotion in virtual environments. In particular, Real Walking (RW) is one of the most effective Virtual Locomotion Techniques (VLT). It causes only reduced cybersickness, but it also requires proportional real walkable space to the virtual one, often requiring wide areas. In this context, optimization techniques have been proposed in the literature, e.g., reorientation or relocation. In this work, a novel method for improving reorientation in a virtual environment, exploiting a dynamic Rotation Gain Multiplication Factor (RGMF) based on the competence of the user in VR systems usage is proposed. The results highlight the effectiveness of the system and show the specific target of users that mainly appreciated it.

Keywords Virtual locomotion technique · Reorientation · Dynamic rotation gain · User experience · Human-computer interaction

1 Introduction

During the last years, consumer devices for Virtual Reality (VR) have become more affordable and introduced a consistent number of users to this technology. Naming industries such as Oculus, Valve, or Sony, the market shows even new versions of their produced devices, such as Head-Mounted Displays (HMDs), with improved characteristics, such as performances and vision quality. In this context, spreading knowledge and consciousness about VR improved its applications. In particular, in gaming Liang et al. (2019); Ye et al.

(2020); Llobera and Boulic (2019), a massive panorama of industrial and research works has been explored for years. This field, one of the first in which VR was involved, shows a noticeable improvement from multiple points of view, underlining how the technology could bring an improvement from well-known standards. This success has increased its usage in different fields: medical rehabilitation Avola et al. (2019, 2018); Turolla et al. (2013), robotics Wang et al. (2020); Burdea (1999); Al-Sada et al. (2020); Martinez-Gonzalez et al. (2019), simulation and training Liu et al. (2018); Ren et al. (2008); Viglialoro et al. (2019); Cohen et al. (2013), entertainment/educational experience Han et al. (2019); Lee et al. (2020) or locomotion redirection/reorientation Bölling et al. (2019); Razzaque (2005); Langbehn et al. (2018). In this extensive context, the latter topic is a relatively new research field in which more experts have always started experimenting with innovative solutions Cardoso and Perrotta (2019). The locomotion study focuses on finding ways for users to move inside a Virtual Environment (VE). In particular, one of the possible choices is to allow the user to walk directly in the real environment, and the identical translations and orientations are repeated in the VE. As expectable, a need occurs: the space optimization. When a large VE is involved, the same space should be needed in the real one to allow the user to move around without obstacles. This

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1:1 ratio is often hard to apply also because in many games, experiences, or simulations, there could be hundreds of m^2 of virtual walkable space. Researchers and industries tried to solve the physical space requirement problem with multiple strategies. For example, Omni by Virtuix Avila and Bailey (2014) is a device that allows the user to walk in place to move his/her avatar in the VE. It shows some strong points, such as the limited space required to make it work. However, the consumer's feeling about its usage is unnatural compared to a real walk. Moreover, it is very constrictive equipment, demolishing the user's comfort level. Similar devices can be listed, but none can provide a freedom feeling, such as if no wearable device is applied to the body (apart from the HMD). This context caused the researchers to find innovative, less invasive, and more transparent solutions, introducing techniques such as redirection and reorientation Al Zayer et al. (2020).

The proposed work improves this topic, providing a dynamic reorientation method based on multiple parameters, such as the user's location in the VE and his/her competence in VR-based applications. The system aims to reduce as much as possible the physical space required by the user for moving inside the VE paying particular attention to the cybersickness (see Sect. 1.2). The algorithm has been tested with VR experts and novices to collect results from heterogeneous typologies of users. Qualitative and quantitative evaluations have been performed exploiting well-known strategies in this field: the Simulator Sickness Questionnaire (SSQ) Kennedy et al. (1993), the System Usability Score (SUS) Bangor et al. (2008), and the Witmer presence questionnaire Witmer and Singer (1998). The paper is structured as follows: in Sect. 1.1, an overview of redirection and reorientation techniques is shown. Following, in Sect. 2, the proposed method is presented. Section 3 lists the experiments underlining exploited tools, environments, and procedures to retrieve relevant information. Finally, the conclusions are presented in Sect. 5.

1.1 Redirection and reorientation

To introduce the concepts of redirection and relocation in VR, we have to explore the broader area of locomotion. This topic has been vastly treated since the first VR applications Al Zayer et al. (2020). According to the literature, numerous techniques allow the user to move in the VE. Some of those are specifically designed to reduce the sickness effects at the expense of smooth and natural interaction: teleport is one of the most famous techniques of this kind Bozgeyikli et al. (2016). More in detail, it instantly moves the player to near or even far locations by pointing at them. It does not generate any smooth translation from the origin to the destination. This technique is commonly used in almost any game or experience for its guessability and ease of use. Moreover,

by exploiting it, the user is not steering at all, but he/she stands in place and directly teleports to the selected locations. When a movement in VE occurs and, in particular, a HMD is involved, cybersickness is always present. As further explained in this document (Sect. 1.2), it is often proportional to the translation speed and the mismatch between real and virtual movements Clifton and Palmisano (2020). Thus, even if a direct teleport to a location hugely differs from a natural walk, it almost completely removes cybersickness. However, the presence feeling of the users vanishes, underlining that they are in a simulated environment. To balance the presence and the cybersickness, other Virtual Locomotion Techniques (VLT) have been proposed over the years: steering-based, manipulation-based, and walking-based methods. As mentioned in Al Zayer et al. (2020), the first one involves tools allowing the user to slide or translate into the VE without moving the entire body. The second one, instead, involves the manipulation of the environment to rotate, resize, and translate it, allowing the user to explore the surroundings without physically or virtually moving. The last VLT is the most natural one. It involves a real physical walk to move the user in the VE. Different methods are proposed in this field, from locomotion in place Templeman et al. (1999) to direct movement mappings and many others LaViola Jr et al. (2017). Thus, all the techniques that differ from the real-walk highlight advantages (e.g., faster movement) and disadvantages (e.g., background knowledge requirements for their usage), but the real-walk based VLT is one of the best techniques in terms of cybersickness impact Al Zayer et al. (2020) (See Sect. 1.2). For instance, the steering translation allows the user to understand the movement direction but could easily provide cybersickness; teleportation is very fast in traveling but hard to manage and track the traveled path. In this context, some of the most recently appreciated by researchers and developers are redirection and reorientation-based techniques Suma et al. (2012); Prinz et al. (2022). Both strategies are often combined to obtain more effective results. The aim is simple: reduce the real space the user requires for directly walking in the VE. This goal can be reached by exploiting a mismatch between the user's real and virtual movements. For instance, in Bölling et al. (2019), the authors proposed a fine-tuned redirected walking strategy to modify the actual direction of a straight walk in VE. In this work, they exploited multiple runs for each user to collect thresholds and modify the rotation gain (RG) factor accordingly. In other words, the trajectory the user follows in real space is a curved path, but he/she feels like walking straight forward in the VE. The results collected by the authors show that the user slightly sensed the mismatch between real and VE. In particular, in the first runs, the feeling was particularly evident. After a gain tuning and a minimum adaptation, the uncomfortable feeling decreases. This work underlines how the RG parameter can be tuned

to balance the presence effect and real space optimization. Another recent work Li and Fan (2020) shows how walking trajectory prediction and playground map knowledge can help to perform redirections when needed. This dynamic approach is based on the specific application of subtle curvature gain. The VE is mapped in a grid in a preliminary phase to define wall locations and possible paths. Then, during the execution phase, the algorithm calculates the position and walking direction of the user for each performed movement and decides the redirection operation. The physical space needed for walking in the VE is noticeably decreased, and, against expectations, the cybersickness results are also positive. Our work was inspired by some of these techniques, collecting strength points from them and providing an improvement. In particular, we selected the real-walk VLT as the ground base of the navigation method for improving the user's natural interaction while we exploited the redirection technique to slightly reduce the required physical space, focusing on cybersickness.

1.2 Cybersickness

The study of motion sickness effects comes from late 20th century Warwick-Evans et al. (1998), where sensory conflict and postural instability are involved. It seems to be caused by the conflict between the current pattern of sensory inputs about self-movement and the expected pattern based on previous experience. It derives from physiology studies and theories about sensory conflict Reason (1978); Reason and Brand (1975), neural mismatch Reason (1978), and postural instability Stoffregen and Smart (1998); Riccio and Stoffregen (1991). Currently, the literature is still studying the susceptibility to motion sickness Golding (2006); however, recent studies Mazloumi Gavvani et al. (2018) classified the sickness related to motion in VR as “cybersickness.” Cybersickness is similar to traditional motion sickness experienced in virtual environments and contains symptoms such as nausea, headaches, or dizziness. Thus, it could also be measured according to metrics provided for motion sickness intensity. Motion sickness experienced in VR has also been referred to as VR sickness, visually induced motion sickness, or simulator sickness; however, in the context of this paper, these adverse symptoms will be referred to as cybersickness. There is a correlation between Virtual Locomotion (VL) and human physiology. The user that is virtually moving in a room but is physically standing in place or following different paths could be affected by slight or even intense uneasiness. As previously mentioned, it does not occur (or is strongly reduced) when a teleporting technique is involved Clifton and Palmisano (2020). On the contrary, when a steering or real walking action is required to perform a movement in the VE, there could be a mismatch between physical and virtual feelings that the user can perceive. This

fact can cause what is usually termed cybersickness Regan (1995). It is related to multiple factors, from latency between head movement and shown images on the HMD Raaen and Kjellmo (2015) to physiological characteristics of each user Munafo et al. (2017). Generally, we can define this disorder as a lack of information between what the brain expects and what occurs. In particular, the cerebellum is involved when a walking action is performed. Combined with the ear labyrinth, it is responsible for the equilibrium and stability of the human body. If visual and auditory information provides specific inputs, the human brain elaborates them, expecting a correspondent feeling and preparing the body to balance. In the case of a strong mismatch between expectations and reality, there could be a proportional awful reaction. In other words, people without labyrinthine vestibular function do not experience motion sickness, indicating that the vestibular system always contributes to nausea. Kim and Park (2020).

We can affirm that nowadays, there is no perfect system that can avoid those side effects in VR, even if some critical improvements have been performed: higher display resolution and refresh rate, faster head tracking sensors, or high precision positional and orientation detectors.

To quantify the amount of sickness felt while running a specific VR-based application, a questionnaire is developed by Kennedy's research group Kennedy et al. (1993). It exploits a table in which some well-known undesired effects are reported and graded for each weight factor that could be associated with it. This document deeply analyzes the questionnaire in Sect. 4.2.1.

1.3 Dynamic RG

The RG can be tuned to control the cybersickness and provide space optimization. According to literature Nilsson et al. (2018); Schmitz et al. (2018), it consists of the mismatch between a real rotation performed by the user and a virtual one. A simplified example is shown in Fig. 1, where both different angles generated from two rotations are visible. We must underline that the RG enhancement or reduction is usually performed only on a single axis,

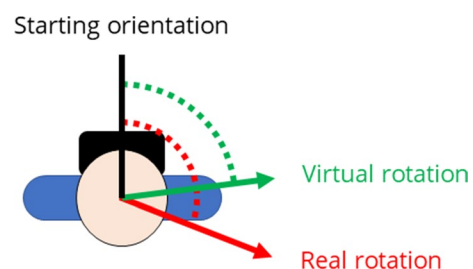


Fig. 1 Different angles generated from real and virtual (reduced) RG

perpendicular to the terrain one. Pitch and roll axes are ignored, and only yaw is involved.

Only a few works in literature are focused on this strategy compared to all the VL ones. However, we must consider that this field is relatively new; thus, many possible solutions could be provided. For example, the authors of Ragan et al. (2017) proposed a method for enhancing RG in virtual space to search for specific objects in the VE. The experiment has a double aim: propose a technique for optimizing space consumption and study cybersickness on mismatched rotation. Moreover, the researchers tested the results on two different displays, a HMD, and a CAVE-like surround-screen Cruz-Neira et al. (1992). The final thoughts of users about the systems were quite surprising because most of them preferred the amplified RG CAVE-driven version instead of the HMD-based one. However, the users that liked the HMD most did not notice significant changes between the use of direct 1:1 rotation and 1.5x multiplying factor enhanced one. This critical consideration proved that the highlighted issues about RG on HMDs are not principally related to the factor but the specific technological tool involved. However, this theory has been partially studied in Zhang and Kuhl (2013), where the effects of dynamic RGs on users with HMDs are analyzed and reported. Each user's sensitivity must be cared for to obtain optimal results regarding the combination of rotation enhancement and cybersickness. However, concerning the RG factor, another study Steinicke et al. (2010) showed how a maximum value of $\times 1.24$ seems more suitable when HMDs are involved to effectively fight cybersickness. We decided to refer to this work to obtain the best results in terms of experience quality for the user. There is still a debate about the best or highest RG bearable values. For example, another study Freitag

et al. (2016) talks about $\times 1.18$ in a CAVE-like environment, contrary to the previously mentioned document.

Another essential work Sargunam et al. (2017) shows how RG could be exploited for reducing physical space during VEs explorations. In particular, the authors underlined the effectiveness of this technique in a controller-based virtual walking condition. In practice, the users were able to move in the VE through the use of a joystick while sitting on a chair. For looking around, instead, a robust RG amplification was applied on the HMD tracker. The results show a discrepancy among users' judgments based on their feelings, but most participants considered the proposed solution an acceptable compromise between presence and sickness. However, due to the noticeable drawback, the system still seems far from a comfortable setup for daily usage.

2 The method

The trajectory analysis is a starting point to introduce the topic and clarify some essential aspects of the proposed method. It tracks the user's virtual and real movements in both environments. Those two parallel scenarios allow evaluation of the discrepancy between the real movement performed by the user and the reproduced one in the VE. The tracking is performed by exploiting the HMD's positional location in the VE and an Indoor Positioning System (IPS) attached to the body of the user for the real location.

In Fig. 2, the possible trajectories traveled by a user are shown. In those three top views, the real path, in yellow, and the virtual one, in black, that the user went through show different applications of RG. Each latter is defined with angles α and β . In example (a), the same gain is set in real and VE. The angles between the user's starting position and target

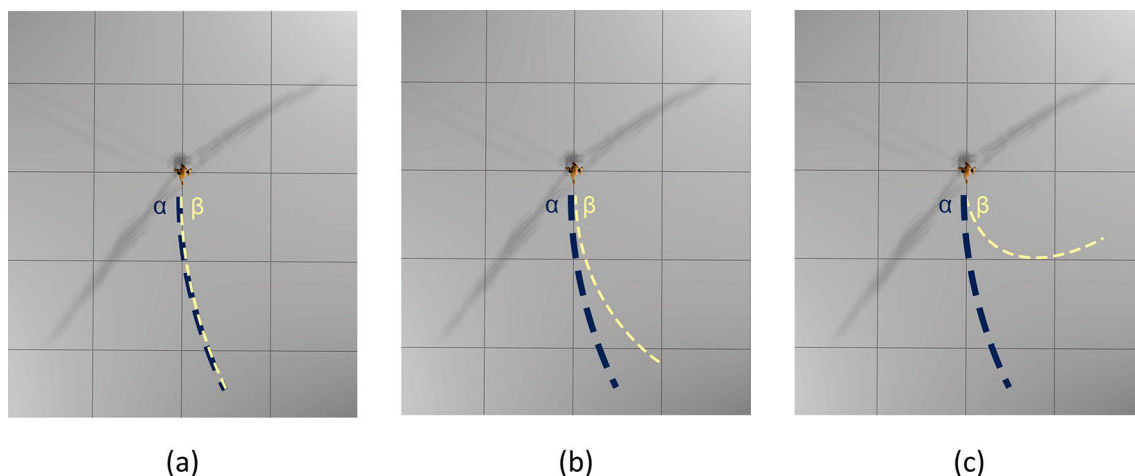


Fig. 2 Trajectories traveled in real (yellow) and virtual (black) worlds. by the user. In each environment, the rotation angle is, respectively, defined with symbols α and β (Color figure online)

location are the same ($\alpha = \beta$). In the second scenario, there is a slight mismatch between the two gains, forcing the user to perform a curved trajectory in the real world to reach the same location in the VE ($\alpha > \beta$). Finally, in example (c), the virtual RG is extremely enhanced, and the user performs a very curved trajectory ($\alpha \gg \beta$).

Angles α and β represent a simplification of a more complex formulation. According to Steinicke et al. (2009), one of the most relevant works in this specific application area, the RG is defined as follows:

$$g_R := \frac{R_{\text{virtual}}}{R_{\text{real}}} \quad (1)$$

where R_{virtual} and R_{real} are:

$$R_{\text{virtual}||\text{real}} := (\text{pitch}_{\text{virtual}||\text{real}}, \text{yaw}_{\text{virtual}||\text{real}}, \text{roll}_{\text{virtual}||\text{real}}) \quad (2)$$

it means that the previously mentioned rotation angle β is defined as follows:

$$\beta := g_R \cdot \alpha. \quad (3)$$

In this context, the RG can be applied during translation, generating a curvature gain (CG). It is required when, for example, a real curve path seems straight in the VE. A circular arc can define the curvature with radius r , so the formula of CG can be defined as follows:

$$g_c := \frac{1}{r} \quad (4)$$

when no CG is applied, $r = \infty$; otherwise, there is an indirect proportionality between CG and radius.

Those theoretical elements provide the base of our study. The system we propose in this work aims to reduce a user's real space to move in a VE without compromising comfort levels or presence effects. It is inspired by other similar works, such as Bölling et al. (2019). As described in Bruder et al. (2012) and mentioned in Sect. 1.1 of this document, only one spatial axis is involved when the redirection is usually applied. Considering the VE tridimensional space, we could assign x and z to the terrain plan and y to the height. Regarding angular rotations, each has a specific nomenclature: *pitch*, *roll*, and *yaw*. In this scenario, y is the height that corresponds to *yaw*, the axis around which the RG modifier is applied.

We exploit this parameter to develop a dynamic RG algorithm that reduces the space required by the user to walk in the real environment without compromising the quality of the experience. However, the same strategy could be applied to the other two axes to obtain the same result in a full 3-D spatial environment (useful in a flight simulator or similar contexts). The principle of our method is

based on two factors: the position of the user's avatar in the VE and his/her view direction. The idea is to reduce the rotation of the user's head to perform a wider rotation in the VE through a positive increment of a RG multiplier. However, the challenge consists of finding the correct red enhancement amount to obtain the best result with the lightest cybersickness. If the value is unconditionally set a priori, it could produce too much mismatch between the real and the virtual rotations, causing uncomfortable disorders in the user. On the contrary, with a too-low value, the benefits of space optimizations could be almost nullified. So, a trade-off is required. Therefore, a presumptive value could be difficult to set properly and demonstrate its effectiveness in every circumstance. Thus, the proposed method assumes that a dynamic RG could be applied, in real-time, while the user is moving in the VE. Accordingly, after a preliminary retrieval of the maximum RG enhancement, we propose a linear decrease in the RG multiplier based on the viewpoint of the user's avatar.

As explained in Sect. 3, the process consists of two phases: calibration and running phases. The user's competence in HMD usage is evaluated and classified in the former. According to Paludan et al. (2016), a possible way of performing this operation is to exploit users' feelings with three different RG enhancement values. By doing so, it is possible to assign the most suitable value to each user, mapping it to a scale of RGs in a predefined range. Instead, the dynamic RG technique is applied in the running phase based on the collected results in the previous phase. In Fig. 3, a schematic overview of the architecture of the proposed system is shown.

2.1 The proposed dynamic RG

In order to perform the proposed dynamic RG during the running phase, some required values are calculated. The procedure can be summarized as follows:

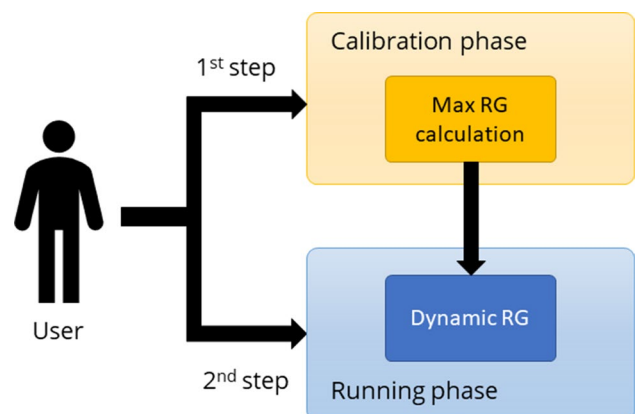


Fig. 3 Architecture of the proposed system

- Considering the environment in the top view, the virtual space's centroid defines the center of a circle whose diameter connects the opposite farther walkable places on the map. This circle defines the dynamic rotation enhancer (DRE) value (explained below);
- The raytrace based on the viewpoint of the user's avatar is calculated;
- Tracking a line between the user and the center of the DRE, we can retrieve the angle γ between the viewpoint raytrace and that line.
- The user's avatar position is calculated. It involves two axes, x , and z , referring to the positional space to the terrain only;
- The distance d between the user's avatar location and the center of the DRE is calculated.

In the end, a circle for defining the DRE, an angle γ , and a distance value d are collected. The DRE can be conceptually linked to the CG.

The following step defines proportions between distances/angles and percentage values. This procedure keeps the formula in a parametric form.

The angle γ defines the difference between the viewpoint direction of the user and the location of the center of the DRE. Consequently, its value cannot be greater than 180° since the minimum dimension is 0° when the user looks at the center of the DRE and 180° when it looks at the opposite location. A graphical example is shown in Fig. 4.

The percent relative range calculation can be performed as follows:

$$PRR(\gamma) := \frac{(\gamma - 0) \cdot 100}{180 - 0}. \quad (5)$$

The same process is performed for the distance between the user's avatar position and the center of the DRE. The formula is:

$$PRR(d) := \frac{(d - 0) \cdot 100}{r_{DRE} - 0} \quad (6)$$

where r_{DRE} is the ray of the DRE. Consequently, a weighted average between those two percentage values is calculated. During the experiments, we noticed that the angle γ was more relevant than the distance d in evaluating a dynamic rotation gain (DRG). In particular, we empirically retrieved a proportion of 8 over 2. Then, the combined percentage value is:

$$PRR_{wa} := 0.8 \cdot PRR(\gamma) + 0.2 \cdot PRR(d). \quad (7)$$

This element is exploited in the final formula for defining the DRG:

$$DRG := \left(PRR_{wa} \cdot \frac{(RG_{max})}{100} \right) \quad (8)$$

where RG_{max} is the maximum value of the rotation gain that the user can bear. It is calculated in a preliminary calibration phase with specific tasks. Figure 5 shows an example of a DRE area, where a virtual room is involved. Both the centroids of the room and the DRE area are overlapped. A stronger red color of the circle corresponds to a higher RG till it reaches its maximum value RG_{max} .

3 Experimental environment

The experimental environment has been set to provide discrete space management. We staged a $25m^2$ room with the required equipment and reserved a $20m^2$ space for the effective locomotion area. Twenty-eight volunteer users joined the experiment. They have different ages, genders, and background experience with VR technology. We collected their information in Table 1. They have been selected according to availability with an internal call in our University. Some participants are Department colleagues, others are students,

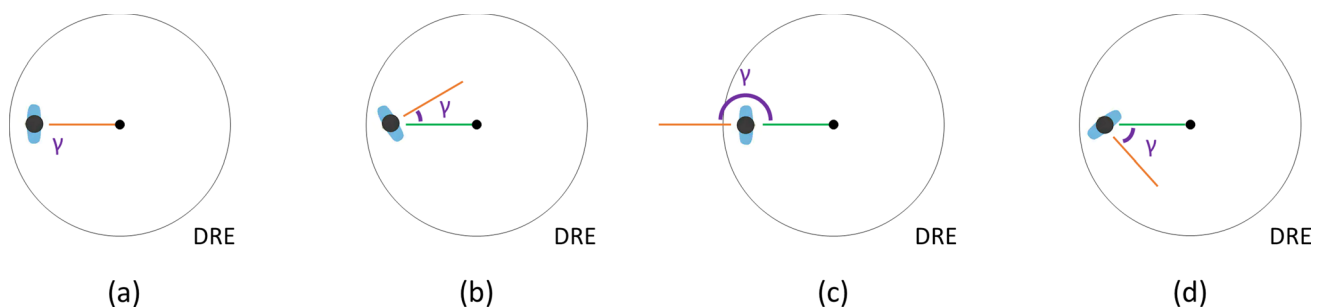


Fig. 4 Explanation of γ angle calculation. In (a), the angle between the user's avatar viewpoint and the tracked line from its position to the center of the DRE is 0° . In example (b), the user turned his/her head to the left and γ assumed a specific value. In (c), we can observe

the maximum value that γ could have when the user looks in the opposite direction of the DRE center, 180° . Finally, in (d), if the user is looking on the right, γ obtains a value between 0° and 180° again



Fig. 5 Example of DRE area calculation. In particular, Fig. 5a shows the involved environment, and Fig. 5b the overlap of the DRE area. The latter is radially filled up for underlining its linear increment function

and another group comprises technical/administrative staff. However, their job profiles can be considered not relevant due to a missing connection with the VR field. Moreover, there is no social class homogeneity among the participants.

A deep discussion is conducted in the following sections, where the effectiveness of the proposed method is analyzed for relevant users' categories (competence level and age). Regarding competence level, the user provides this preliminary information according to his/her confidence with VR technology. However, we preferred to prove the actual competence of each one of them during the testing phase. The final discussion compares expectations based on preliminary user judgment and absolute competence. We decided to collect this information because there could be a correlation between cybersickness susceptibility and users wanted to VR Rangelova et al. (2020).

Consistently to Sect. 2, the experiments were conducted in two steps: the first consists of a calibration phase and the second in a running phase. The calibration determines the RG_{max} value. We did not consider the answer about the competence in VR that the users provided during the registration. The task was performed by completing pre-exposure sections of the Simulation Sickness Questionnaire (SSQ) Kennedy et al. (1993), deeply analyzed in section 4.2.1, to determine a baseline measurement of their current experience of adverse symptoms. This parameter is exploited in the second phase, the running one. The users are introduced to a specific environment where the proposed rotation gain enhancement is applied, and a task must be completed. During the entire phase, continuous feedback is required from the user to evaluate the sickness and stress status. It is not exploited as a metric for the evaluation but just for an informal check from the operator to avoid critical situations (e.g., falls to the ground,

dizziness, or nausea), especially when the max RGMF is exploited. Other similar works inspired the proposed methodology and metrics in literature Rahimi et al. (2020); Fussell et al. (2019).

3.1 Tools and equipment

The system used for developing and testing is based on a high-end desktop computer composed of an AMD Ryzen 7 3700X CPU, 64GB of RAM, an NVidia RTX 2080ti, a Samsung SSD 970 PRO hard drive, and a motherboard capable of USB 3.1 high-speed connections. Those specifications are computationally powerful enough to support the development and the execution of VR-based experience. This equipment is specifically selected to reduce the delays caused by insufficient hardware, supporting the validation of the proposed method. About the VR headset, the Oculus Quest 2 has been involved. It is one of the best devices for this kind of study due to its complete autonomous software management. It means that no wires or computers are required to make it work. Moreover, it is possible to exploit $20m^2$ wide areas, keeping a good quality tracking of positional space and orientation of the user. It supports 6 degrees of freedom (6DoF) head and hand tracking through integrated Oculus Insight (inside-out tracking) technology. It presents four front-facing cameras for visual controller tracking, gyroscopes, and accelerometers. Unlike other technologies, no IR external sensors (e.g., old Oculus devices or HTC ones) are required. However, the final experimental environment provided a connection between the HMD and the computer to nullify any possible software delay. The wire was placed over the head of the user, dynamically hooked to the ceiling.

Table 1 Volunteer user list, where three important parameters are specified: age, gender, and VR background experience.

User ID	Age	Gender	VR experience	Visual impairment
1	22	Male	1	no
2	27	Female	2	no
3	27	Male	1	no
4	25	Male	0	no
5	32	Male	3	no
6	23	Female	1	no
7	38	Female	3	no
8	37	Male	2	no
9	55	Male	1	no
10	41	Male	0	no
11	31	Male	0	no
12	30	Male	1	no
13	31	Male	0	no
14	34	Female	1	no
15	20	Female	2	no
16	21	Male	2	no
17	32	Female	1	no
18	32	Female	0	no
19	33	Male	3	no
20	38	Male	3	no
21	62	Male	2	no
22	58	Female	1	no
23	46	Male	2	no
24	47	Male	1	no
25	46	Female	3	no
26	23	Male	0	no
27	42	Male	0	yes
28	27	Female	0	yes

The latter is previously collected by identifying the user competence in VR-based applications and classifying it as follows: 0 - none, 1 - minimum competence, 2 - medium competence, and 3 - expert/daily usage

3.2 Calibration phase

Before proceeding with the calibration phase, we collected some medical information about the relationship between each patient and sickness in general. A specific medical check provided results about Pre-Exposure Background, Pre-Exposure Physiological Status, and Pre-Exposure Symptoms Sharples et al. (2008). All those exams underlined that no critical health condition was detected to avoid fake results. Moreover, all the volunteers were healthy from a psychomotor point of view. However, the two users affected by a slight visual impairment (subject 27 is affected by the myopia of category 1 severity in the World Health Organization (WHO) scale, and subject 28 is affected by presbyopia with

the right eye lens strength of +1.75 and the left eye of +2.00) have been separately studied from the other users. All the participants have been seen by specialized medical staff from Policlinico Umberto I hospital.

The calibration phase was inspired by another work Farmani and Teather (2020), where the authors provided a simple but effective method for retrieving information about users' sickness sensitivity. It collects feedback about personal comfort levels felt during specific task execution. In particular, the latter comprises numerous sub-runs, where the user rotates his/her head in the VE with different RGs. At the end of each one, the authors collected information about the experience felt. Our proposed approach is similar, aiming to obtain the highest value of RG_{max} bore by the user. We designed this method to find the most suitable threshold for each user, adapting the system to their physiology. According to mentions in Sect. 1.3, a rotation gain multiplier factor could reach the maximum value of $\times 1.24$. Some cybersickness contraindications could occur if we overcome them. Thus, we can determine the highest rotation gain multiplier factor at a maximum distance from the center of the DRE for the most expert VR user as $\times 1.24$. This value is proportionally reduced for users with less competence in VR-based applications to keep a RG enhancement while mitigating cybersickness. We introduced a parameter not based on the VR experience value collected in the preliminary phase and provided a fine-tuned RG value for each user. We assumed the personal assessments could be disputable due to the lack of objectivity. Thus, we calculated the competence levels of each participant with the proposed pipeline and compared them with the ones declared in the preliminary phase. The actual competence of the user, differently from the personal opinion provided in the preliminary questionnaire, is calculated over the sickness feelings in different tasks and diverse rotation gain multiplier factors. More in detail, according to Farmani and Teather (2020) results, the sickness seems linearly dependent on the rotation speed and consequently the gain. This fact allows us to suppose that if we assume a ranged scale from 1 to 10 to determine the competence level of a user in VR, on a value of 10, the maximum bore rotation gain is $\times 1.24$ and, on the contrary, on value 1 it assumes the multiplication factor $\times 1$ since the user is susceptible to cybersickness. The formula 9 shows how the proportion is calculated

$$RG_i = \frac{(CompetenceLevel - CompetenceLevel_{min}) \times (RG_{max} - RG_{min})}{CompetenceLevel_{max} - CompetenceLevel_{min}} + RG_{min}, \quad (9)$$

where i is the searched value, RG refers to the rotation gain multiplier factor (RGMF), and $CompetenceLevel$ is the value in the competence level range.

Table 2 Range scale of proportional user competence in VR interaction associated with each RGMF

Competence level	1	2	3	4	5	6	7	8	9	10
RGMF	1	1.02	1.05	1.08	1.11	1.13	1.17	1.19	1.21	1.24

Fig. 6 Environment exploited in both calibration and running phases. The original Unity3D asset can be downloaded from: <https://assetstore.unity.com/packages/3d/environments/urban/abandoned-asylum-49137>



Fig. 7 Top view of the environment. As shown, there are numerous rooms and sections. This subdivision was useful in multiple circumstances, from a motivational point of view for the user to size-specific requirements

Therefore, the complete proportional scale is provided in Table 2.

The VE in which the tasks of both calibration and running phases were executed can be overviewed in Figs. 6 and 7.

We decided to exploit such a detailed and characteristic place to improve the presence effect and motivate the users to feel as natural as possible in their movements and reactions.

Thus, always referring to Farmani and Teather (2020), the authors determine the resistance of each user with a continuous rotation for a fixed amount of time. We performed a similar task, providing 10 rotation speeds: 5°/s, 10°/s, 15°/s, 20°/s, 25°/s, 30°/s, 40°/s, 60°/s, 100°/s, and 120°/s. The duration of each trial was 1.2 min. The task could be interrupted at any time. At the end of each trial, the users had to evaluate their sickness (usually nausea or dizziness) effect from 1 to 10, when the lowest value corresponds to “none” and the highest one to “unbearable condition”, requiring an immediate trial cutoff. This approach is similar to the 11-point Misery Scale (MISC) Ng et al. (2020), but in a shorter range of feelings due to the slight differences among the RGMF values. The recovery time between trials was 1.3 min. The entire procedure required about 25 min for each user. The collected results were exploited in a proposed schema to individuate the participants’ best profile in Table 2. For each user, it consists of exploiting a weighted symmetrical average function on all values among the sickness scores of each trial. It is finally rounded and associated to Table 2 according to Formula 10,

$$Sl = \left\lceil 10 - \frac{\sum_{i=1}^{10} ss_i * w_i}{10} \right\rceil \quad (10)$$

where i is the trial, w is its specific weight, ss is the provided score, and the parentheses $\lceil \rceil$ indicate the round function. Concerning the weights, we empirically noticed that the first and the last trials were less significant than the others regarding sickness level information. This fact derives from

boundary situations, where the rotation speed does not cause almost any uncomfortable feeling (first executions) or can completely disorient the user (last executions). In the intermediate cases, the analyzed rotation speeds are the ones that most frequently occur in standard VR-based experiences. Due to that, the trials' weights were distributed as follows:

- Trials 5 and 6: the weight is 5;
- Trials 4 and 7: the weight is 4;
- Trials 3 and 8: the weight is 3;
- Trials 2 and 9: the weight is 2;
- Trials 1 and 10: the weight is 1.

The weight distribution graphically represents a linear and symmetrical spike from its center to the edges. The final results of the calibration phase provided an accurate profile of each user about cybersickness sensitivity and allowed us to determine their most feasible RGMF.

We noticed some direct correlations between the declared VR experience of each user and their susceptibility to cybersickness according to the proposed method. In fact, in most cases, for high VR experience, value corresponds to a high Competence Level score. However, it is interesting to notice that some outliers do not respect this proportionality (e.g., User 5, User 22) and for this reason, the only reliable value is the calculated one.

3.3 Running phase

The running phase is performed the day after the calibration phase. The users needed a sufficient break before continuing the experiment to provide genuine results. In this way, we also tried to make the inexperienced users keep their disinclination to VR and HDMs usage.

The volunteers were introduced to the same environment exploited for the calibration phase when this phase started. Still, we located them in another section of the virtual building and added sounds and dynamic lights. The scene became more realistic, improving the presence effect. In this context, we asked the participants to execute a specific task three times to complete the experiment. In the first trial, we set the RGMF to $\times 1$. The RGMF was set to the maximum value of $\times 1.24$ in the second one. Finally, in the third run, we set the RGMF to the value calculated during the calibration phase for each user. The users in those tasks aimed to collect a hidden key and open a box with it. The key was always located outside the room where the player was spawned. Instead, the box could be hidden in the same room where the user started. Thus, they had to go outside, search for the key, guided by an arrow key on the heads-up display (HUD) that is shown for 5 s in some specific locations, and eventually return to the starting room to open the box. The entire task

did not require any interaction with the environment. Items are collected simply by walking near them, and doors are automatically opened. There are 3 different locations for the key and the box; at startup, the game randomly selects one of those for each item. The areas where the arrow hints are shown are fixed. An example of an involved section of the map for executing this task is shown in Fig. 8.

The execution of each trial required between 2 and 5 min to be completed, depending on the competence level of the user in the VR-based application. There was a recovery time of 15 min between each trial. At the end of each trial, we asked the participants to provide a judgment about the sickness effect felt and the experience in general according to the questionnaires shown in Sect. 4.2.

Those results provided us with qualitative feedback about the proposed method compared with the maximum and the minimum values of RGMF.

4 Results

The results have been divided into two typologies: objective and subjective results. The formers analyze the obtained optimization with the proposed method regarding spatial dimensions. On the contrary, the second ones are related to a user-centered study, in which participants' judgments are discussed to define our algorithm's comfort level. Combining those two studies finally determines the overall awareness of the system. The collected results mainly refer to not visual-impaired participants (the first 26 in Table 1). While for each sub-section, a specific paragraph discusses these cases.

4.1 Objective results

To quantify the space optimization obtained with the proposed algorithm, we have to analyze the real and the virtual paths tracked by the users during the execution of each task of the running phase. We can refer to Fig. 9 to better understand how to proceed in the study. In Fig. 9a, the VE path and the real one comparison for a specific user walks when the RGMF was set to $1\times$ is presented. The red (virtual) and the green (virtual) paths and areas are the same; it means that the ratio between VE and the real one is 1:1. On the contrary, another trial is analyzed in Fig. 9b. As shown, there is a difference between the path walked in VE and the one in the real space. In this example, the RGMF was set to $\times 1.17$, optimizing the occupied space.

The entire area for executing the task was $20m \times 16m$ wide. As shown in Fig. 8, on the top right is a prosecution of the corridor. Still, an invisible virtual wall is placed on its boundaries to prevent the user from trespassing on the available space. We determined the difference among

the areas built based on the paths in Fig. 9b, tracking the required space for both cases. In the VE, the user occupied an area of $18.2m \times 15.2m$, whereas, in the real space, he/she required only $17.5m \times 14.9m$. The reduction is noticeable, $70cm$ on the X axis and $30cm$ on Y one, for $2.1m^2$. This complete sample result shows the optimization effectiveness in terms of space; however, there could be some exceptions, e.g., if the path traveled by the user always overlaps with the radial direction of the DRE. The proposed method does not apply any RG enhancement in this specific case. Though, in a real scenario, it is sporadic that this case occurs. Furthermore, on the other hand, with higher RGMF values and wider areas, optimization is more evident. Our tests on the dataset of users not affected by visual impairments show a space consumption decrement between 0.5% and 1.2% of the virtual space. We also collected results from participants 27 and 28, and we noticed a perfect fitting with the expectations: the visual impairments do not affect the final results. Users required a physical space of $17.8m \times 15.4m$ and $17.6m \times 15.5m$, respectively, to complete the task, proving that the performance of space consumption is not affected by this parameter. Therefore, we noticed that the reduction in the physical space is more evident if the user rotates near the borders of the map: the RG is stronger close to the circumference of the DRE; thus, the higher the number of tasks in its proximity, the greater is the reduction in the required physical space. Moreover, we suppose a wider real area could perform better; this assumption will be investigated in future proposal improvement. No changes can be noticed in an outdoor environment since the HMD completely excludes the interaction with the user's real environment; thus, if the tracking sensors are not affected by sunlight or other environmental noises, the results are the same.

4.2 Subjective results

Conversely, we collected user experience information to compare the proposed dynamic method with the standard static one. According to Fussell et al. (2019), we selected three important tests to evaluate user experience: the System Usability Scale (SUS) Bangor et al. (2008), the Witmer presence questionnaire Witmer and Singer (1998) and the previously mentioned SSQ Kennedy et al. (1993). We reported the users' scores of the first 26 in Table 1 separately from the last two due to the visual impairment affection. A separate section treats this category of users, highlighting some differences. Moreover, in the manuscript's appendix we reported individual data points for each test and user.

4.2.1 Simulation sickness questionnaire (SSQ)

The SSQ Kennedy et al. (1993) is one of the most used scoring systems for detecting the overall cybersickness under a

simulated environment. It can be exploited in numerous contexts, such as cabins for airplane pilot training or immersive consumer entertainment applications. In particular, it can be considered an important parameter when VR applications or tools are novel or naive. Nowadays, this scoring system is still very used, and many of its variants are designed to be more accurate in specific scenarios Kim et al. (2018); however, the original proposal of the SSQ is still one of the most used in VR and non-VR contexts analysis, highlighting its effectiveness still today Kourtesis et al. (2023). It consists of 16 symptoms which are rated on a four-point scale from 0 to 3 ("none," "slight," "moderate," and "severe"). Symptom ratings were aggregated into three categories, Nausea (SSQ-N), Oculomotor (SSQ-O), and Disorientation (SSQ-D), which were accumulated to produce a total score of sickness (SSQ-TS). In other words, each primary symptom is associated with a sub-score, and the final score shows a percentile grade of total cybersickness. The total score (TS) is calculated with a specific formula, deeply explained in the authors' work. Table 4 shows the scores obtained from this test. We calculated the TS for each run explained in Sect. 3.3 and each user to provide minimum, maximum, average, and standard deviation scores. The latter is calculated by exploiting the mean of all standard deviations. As noticeable, the expectations are respected: when the RGMF is set to $1\times$ (No-RGMF), the sickness values are low, while on the highest RGMF (Max-RGMF), the results are the worst. The proposed method is in between those values. However, the latter provided scores closer to the values obtained on No-RGMF instead of Max-RGMF, even if, in numerous cases, the RGMF was set to a relatively high multiplication factor, such as $1.17\times$. In Fig. 10, the graphical representation in chart form of values in Table 4 is shown.

As we can see, two relevant values underline the proposed method's effectiveness: the absolute minimum and the average. In particular, the first parameter is closer to the No-RGMF value than the Max-RGMF. It means that the most resistant user to the sickness effect experienced a low impact of the proposed dynamic method during task executions. The same could be deducted from the average, where the difference between No-RGMF and the proposed one is only 2.4 points, and the Max-RGMF is 5.7 points away. This result is related to the entire dataset of users, from the most to the least resistant to cybersickness. Thus, we can consider it the most relevant information about the effectiveness of the proposed method.

4.2.2 System usability scale (SUS) questionnaire

The SUS questionnaire Bangor et al. (2008) is a simple but effective usability-centered form by which it is possible to retrieve direct judgments from users about their experience in system usage. We exploited this qualitative metric since

its effectiveness as a tool for measuring the level of simulation sickness has been proven in the literature Gálvez-García et al. (2015).

The answers were collected in a scale form, from 1 to 5, respectively, representing a grade from “Strongly disagree” to “Strongly agree”. The median value (3) means neutrality. The collected results are analyzed through the explained technique in Bangor et al. (2008) and finally exposed in a percentile model. As for the SSQ, we asked each to fill out this questionnaire at the end of each of the three tasks, focusing on the specific experience felt in terms of comfort while performing the execution. The summary of the final results is shown in Table 5. The same results are in chart form in Fig. 11.

We notice that the results obtained in this test are similar to the SSQ in proportions: minimum and average scores underline how the proposed method is closer to the No-RGMF than the Max-RGMF. However, we can also denote a different classification of grades. The same percentiles (with different scores) are collected for each value in both No-RGMF and Proposed-RGMF, differently from Max-RGMF. This result highlights the proposed dynamic rotation gain technique’s satisfaction, ease of use, and immediacy. This result is not foregone since a variable RGMF could have disoriented the user while exploring the VE. We can deduce that the collected values derive from combining two main factors: usage habit and the small RGMF. The first is related to the constant slow familiarization that the user is experiencing while performing the task. The human brain can adapt its behavior to the surrounding environment relatively quickly. In this context, a feasible change of natural interaction could only partially impact the user’s feelings without any sensible issue. So, the user seems to be able to easily and quickly adapt to the proposed method after a while. The second reason is linked to the first: a low variation of RGMF is more bearable than a higher one. The calculated factor in the calibration phase balances a trade-off between space optimization and feasible RG for the specific user, applying a greedy approach and obtaining the best result.

4.2.3 Witmer presence questionnaire

We also collected answers from the Witmer presence questionnaire Witmer and Singer (1998) to define the effective presence effect felt by the users. It consists of a form to fill, similar to the previously presented ones but designed to define the simulation’s quality in specific categories: Control Factors, Sensory Factors, Distraction Factors, and Realism Factors. Each one of them is subdivided into other classes. The final results allow us to retrieve an overview of the entire experience regarding “presence.” According to Slater (1999), this word indicates a subjective experience of being in one place or environment, even when one is physically simulated in another. Instead, “immersion”

is a correlated psychological state of the user when experiencing the presence effect.

The original work of the authors inspires this test but is slightly customized to be more suitable for the proposed system and environment.

The answers were collected on a seven-point Likert-type scale, from lowest grade (1 point) to highest (7 points). For some questions, the scale is inverse for keeping the appreciation level on the same scale. As previously performed, we asked the participants to fill out the form at the end of each execution with different RGMF values. The scores are calculated for each category by summing the total result of each question and dividing it by the number of items per category.

Table 6, and Fig. 12 show the final results.

A significant value that we can notice is related to Adaptation/Immersion, where the average of the Proposed-RGMF has exceeded both No-RGMF and Max-RGMF. This fact is particularly relevant due to two critical questions about the system’s usability: 3(b) and 3(h). We should consider that a slight addiction could occur; however, in both questions, the average answers for the proposed method have, respectively, provided a value of 5.8 and 6.1, proving its effectiveness. We can also notice that those results follow the trend of the others, placing the proposed method between the other two. However, the obtained results show its closeness again to the No-RGMF. The users underlined how the intrinsic natural interaction seems to be a preserver, even if a slight redirection function is continuously applied.

4.3 Statistical analysis of the collected results

The collected results have been numerically compared according to simple differences among aggregated values. However, nonparametric statistics, e.g., Friedman’s test, could provide a more relevant interpretation of the differences in cybersickness experienced among each group of users Sprent and Smeeton (2016). The proposed test is similar to the Analysis of Variance (ANOVA) and it is used to test for differences between groups when the dependent variable is ordinal. It is mainly exploited to detect differences in treatments across multiple test attempts; however, we can consider our RGMF the variable that changes for each “treatment”: No-RGMF, Max-RGMF, and Proposed-RGMF, respectively. We applied it to SSQ, SUS, and Witmer scores for each RGMF setting. For significance level $p = 0.05$ (a risk of 5% of concluding that a difference exists when there is no actual difference), we obtain a Friedman X_r^2 statistic of 50.0769 for the SSQ, 47.1346 for the SUS, and 52 for the Witmer test, according to the values in Table 9. In all of them, we obtained a significant result due to $p \leq X_r^2$.

4.4 Discussion about user age and competence level

We highlighted how the classification of users is essential to collect information about the improvement provided by the proposed system. In particular, we discuss three aspects of this analysis: age, personal preliminary background, and competence level inter-class differences.

The first one provides information about the best target users classified by age range. We grouped the participants into three categories:

- Young users: a total of 8 users whose age is between 20 and 29 years old;
- Middle age users: a total of 12 users whose age is between 30 and 39 years old;
- Adult users: a total of 6 users whose age is over 40 years old;

Those classes do not consider any other information than age. For this reason, the results we are showing refer to this parameter. Thus, we must consider that different VR interaction competence levels could also contribute to improving or decreasing the collected scores. At the end of this section, a combined study could determine the relationship between age and competence. Table 7 shows the results for each age class considering the SSQ.

Even if the number of components of each group is different and no actual comparisons among them could be provided, we noticed some relevant information related to age. In particular, as we expected from Saredakis et al. (2020), elder users tend to feel natural in VR, and better bear sickness symptoms. Despite Arns and Cerney (2005) and even if young people seem more adaptive to technology, particularly to VR applications, it seems that the symptoms in those subjects are amplified and usually more challenging to manage. The best score related to the proposed method is collected on users whose age is over 40 years but with a relevant difference of 2.5 and 1.6 points, respectively, in ranges 20–29 and 30–39. This result seems to highlight how the system could be helpful in contexts where elder users are involved. However, we do not have enough data to propose its application in contexts where the targets are third-grade users, also considering that a real comparison among age classes requires the same number of participants for each group.

Another important aspect is the correlation between what users think about their competence level in VR and what it is. Comparing Table 1 and 3, we could observe a kind of coherence between those two parameters. This fact provides some important considerations about the conducted tests. First, the proposed calibration test confirms users' consciousness regarding personal opinions about

Table 3 Competence level and RGMF determined for each user exploiting the proposed technique

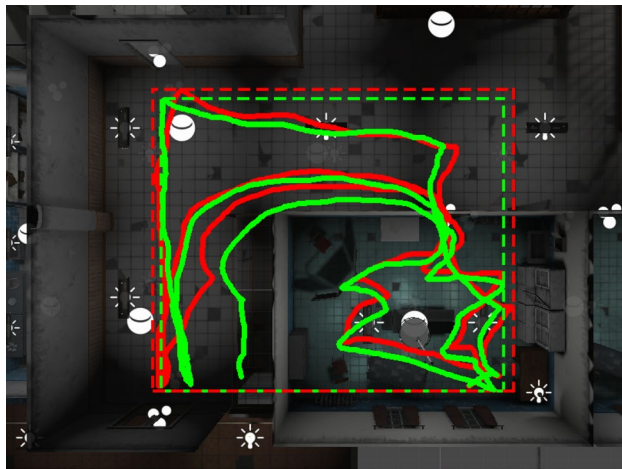
User ID	Compe- tence level	RGMF
1	3	1.05
2	5	1.11
3	4	1.08
4	3	1.05
5	8	1.19
6	5	1.11
7	7	1.17
8	7	1.17
9	5	1.11
10	2	1.02
11	3	1.05
12	4	1.08
13	5	1.11
14	5	1.11
15	6	1.13
16	4	1.08
17	4	1.08
18	5	1.11
19	6	1.13
20	9	1.21
21	7	1.17
22	7	1.17
23	6	1.13
24	6	1.13
25	8	1.19
26	2	1.02
27	4	1.08
28	2	1.02



Fig. 8 Section of the map involved in the specific exercise monitored during the running phase. In this example, we provided some possible spawn locations of the player, the key, the box, and the hint areas, where the arrows are shown on the UHD



(a) Comparison between areas of the real path of the user (in green) and the virtual path (in red) when the RGMF is set to 1 $\times$.



(b) Comparison between areas of the real path of the user (in green) and the virtual path (in red) when the RGMF is set to 1.17 $\times$.

Fig. 9 Real and virtual areas comparisons when RGMF= 1 $\times$ and RGMF= 1.17 $\times$ retrieved tracking the paths of user 8 during his run

Table 4 SSQ summarized results for the first 26 users in Table 1.

	No-RGMF	Max-RGMF	Proposed-RGMF
Min	2.1	6.8	3.3
Average	6.2	14.3	8.6
SD	3.7	3.9	3.5
Max	17.3	22.4	18.5

Values of minimum, maximum, standard deviation, and average are collected for each different RGMF after all executions. The minimum and the maximum are the absolute values (outliers). Instead, the average and the standard deviation refer to the average of all users

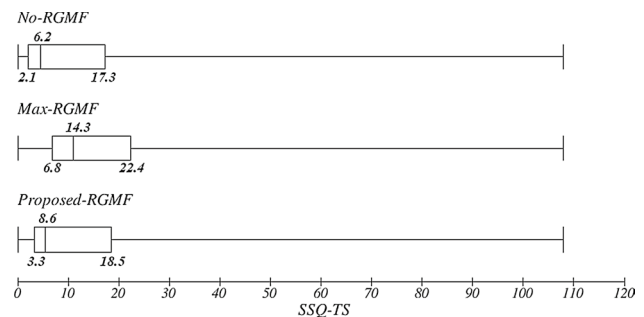


Fig. 10 Graphical representation of the retrieved SSQ-TS summary for each RGMF for the first 26 participants in Table 1. The range of the values is between 0 and 108. The bars represent minimum, maximum, and average values. The minimum and the maximum are the absolute values. The average, instead, refers to the average of all users

Table 5 SUS summarized results. Minimum, maximum, average, and standard deviation values are collected for each RGMF after the executions of each of the first 26 users in Table 1.

	No-RGMF	Max-RGMF	Proposed-RGMF
Min	76.6	68.0	73.7
	Grade B	Grade C	Grade B
Average	85.6	78.5	83.0
	Grade A	Grade B	Grade A
SD	4.1	6.1	3.9
Max	93.1	89.1	91.2
	Grade A	Grade A	Grade A

The values on top are expressed in terms of SUS score, and the ones on the bottom are the matching percentile grades (from F to A, respectively, representing “Awful” and “Excellent”). The minimum and the maximum are the absolute values (outliers). Instead, the average and the standard deviation refer to the average of all users

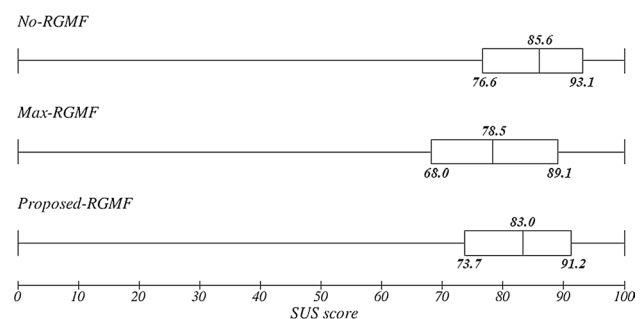


Fig. 11 Graphical representation of the retrieved SUS summary for each RGMF in Table 5. The bars represent minimum, maximum, and average values. The minimum and the maximum are the absolute values. The average, instead, refers to the average of all users

the collected experience in VR interaction. Therefore, the execution of tasks during the running tests was conducted without any strain since there was no challenge or particular request they had to satisfy. We, as testers, were not

Table 6 Witmer presence questionnaire summarized results.

	Involvement			Sensory Fidelity		
	No-RGMF	Max-RGMF	Proposed-RGMF	No-RGMF	Max-RGMF	Proposed-RGMF
Min	65	59	63	30	17	25
Average	75.0	64.9	69.8	36.2	24.9	28.7
SD	3.7	3.5	3.6	2.8	3.3	3.6
Max	82	72	78	41	30	38
	Adaptation/Immersion			Interface quality		
	No-RGMF	Max-RGMF	Proposed-RGMF	No-RGMF	Max-RGMF	Proposed-RGMF
Min	42	20	23	16	6	12
Average	45.3	30.2	47.7	19.2	14.2	16.7
SD	5.3	4.5	5.0	1.1	3.5	2.2
Max	53	40	50	21	21	21

Minimum, maximum, average, and standard deviation values are collected for each RGMF after the executions of each of the first 26 users in Table 1 and for each class. The minimum and the maximum are the absolute values (outliers). Instead, the average and the standard deviation refer to the average of all users. The maximum that can be obtained for each category is: Involvement → 84; Sensory Fidelity → 42; Adaptation/Immersion → 56; Interface Quality → 21

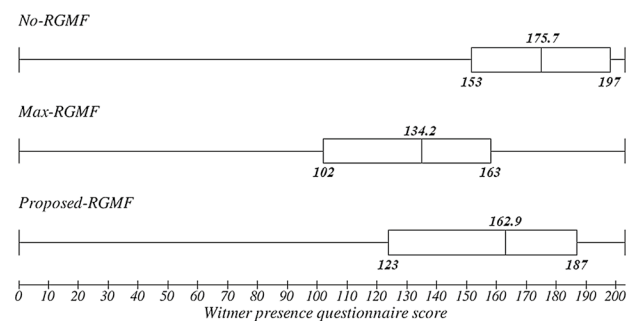


Fig. 12 Graphical representation of the retrieved Witmer presence questionnaire summary for each RGMF in Table 6. The bars represent minimum, maximum, and average values. The minimum and the maximum are the absolute values. The average, instead, refers to the average of all 26 users. The total maximum that can be obtained is 203

Table 7 The average of each class of ages and RGMF for the SSQ of the first 26 users in Table 1.

Age Range	No-RGMF	Max-RGMF	Proposed-RGMF	Average
20–29	6.5	15.2	9.8	10.5
30–39	6.2	14.5	8.9	9.9
>40	6.3	13.4	7.3	9.0

No comparisons can be provided due to the different number of components for each group

expecting more than what they declared in the preliminary questionnaire. The context inducted them to be relaxed and behave most naturally. Thus, the collected results can be considered truthful and genuine.

Table 8 Comparison between the average of each class of competence level and RGMF for the SSQ for the first 26 users in Table 1

Age Range	No-RGMF	Max-RGMF	Proposed-RGMF	Average
Low competence: 1–4	7.8	18.7	9.2	11.9
Mid competence: 5–6	6.1	15.6	8.1	9.9
High competence: 7–10	5.2	9.0	7.4	7.2

Then, we analyzed the results obtained based on users' competence always referring to the first 26 participants in Table 1. Three classes have been set, where levels have been grouped in ranges. In particular:

- Low-level competence: this group contains nine users with competence levels between 1 and 4 according to Table 3, where the RGMF range goes from $\times 1.05$ to 1.08 ;
- Middle-level competence: this group contains ten users with competence levels between 5 and 6 according to Table 3, where the RGMF range goes from $\times 1.11$ to 1.13 ;
- High-level competence: this group contains seven users with competence levels between 7 and 10 according to Table 3, where the RGMF range goes from $\times 1.13$ to 1.24 ;

The proposed classification is quite balanced and offers an overview of the method's effectiveness based on users' VR tendencies and background. Table 8 shows the results for SSQ and each RGMF classified per competence level.

As visible, an important consideration can be deduced; the proposed method difference in score for each competence

level class is low. In particular, analyzing the distance between low and middle competence, those two classes are just 1.1 points from each other. This result suggests how the system could be very effective for inexperienced users, bringing the benefit of space optimization without compromising the experience.

Concerning the correlation between age and competence, we can consider that mid-age users with high competence levels enjoyed the proposed system more than younger users with the same competence (and vice versa). However, it is interesting to analyze the comparison between the young users with high competence and the older ones with low competence. In this case, the competence factor overbears age. Young trained users of VR interactions are more adaptive to changes and can more easily manage the RGMF than elder ones.

In conclusion, all the obtained results suggested that the proposed method seems suitable for contexts involving inexperienced adult users, e.g., medical rehabilitation, personal daily aerobic exercises, and virtual museum tours.

4.5 Qualitative results for users affected by visual impairment

Differently from the quantitative results, the qualitative highlights some relevant differences between visual impairments affected and not affected users. To this aim, we collected the SSQ and the SUS questionnaire from users 26 and 27. In particular, for the SSQ we noticed that both users provided average higher scores for No-RGMF, Max-RGMF, and Proposed-RGMF (7.1, 14.8, and 8.9, respectively); it means that they are more sensitive to the RGE, but we can also highlight that there is an evident closeness between the No-RGMF and the Proposed-RGMF scores, according to the results obtained with the other users' segment. Also, the SUS provided similar results to the previously observed ones, where the average of No-RGMF, Max-RGMF, and Proposed-RGMF are 82.8, 79.7, and 80.9, respectively. In general, we noticed that even if the users affected by visual impairment provided lower scores, the results for the proposed RGMF are always closer to the $\times 1$ RG than the maximum RG, proving the method's effectiveness.

4.6 Discussion

Concerning the collected results, some considerations could be provided. We noticed that there are some correlations between the three different RGMF values and the users' classifications: as expected, the higher the competence level, the higher the tolerance to the RGE. However, we can also highlight some unexpected results. Assuming that with the same competence level the age seems a determinant factor, there

could be multiple reasons why untrained adult users are more comfortable than young ones. According to Tian et al. (2022), the age difference cannot be a powerful indicator of cybersickness. However, the authors highlight that very young users are more susceptible to cybersickness, which slowly decreases over the years. Thus, the hypothesis that the adult subjects involved in the study were subjectively more resistant to cybersickness seems more realistic. Concerning the spared physical space, the obtained results in a $20m^2$ walkable area are not very satisfactory. However, we must consider that the proposed task was not designed to optimize the results; moreover, this work focuses on keeping the cybersickness as low as possible. In this sense, the proposal seems to accomplish the task due to the higher closeness between Proposed-RGMF and No-RGMF qualitative scores than Proposed-RGMF and Max-RGMF ones. In conclusion, we must underline that the number of involved participants is not statistically relevant. In fact, a group of only 28 participants could be considered below a standard threshold of a significant population for a robust statistical analysis Singh and Masuku (2014) (usually around a minimum of 100 subjects Sudman (1976)). Thus, we aim to provide more details about the effectiveness of an improved version of our proposal in future developments involving larger areas, a greater number of participants, and novel evaluation metrics.

5 Conclusions

In this work, we presented a novel method for redirecting users in VR environments while walking in real space. It aims to optimize the occupied area while moving around, offering an enjoyable experience and stemming cybersickness. In particular, it exploits a calibration phase to obtain information about the users and their competence in VR-based systems usage. The collected parameter allows setting a RGMF value to reach the proposed aim. The tests with widely used evaluation methods, such as the SSQ or the SUS, provided promising results. The main target of the users' category seems to be those over 40 years old ones, and no competence in VR-based applications is required. Moreover, the system's modularity invites us to improve it in future research. Our next steps could be to increase the walkable physical space and to introduce an automatic method for recognizing the competence level of each user during the calibration phase.

Appendix: individual data points

In this appendix, we reported the individual data points retrieved by each user. We provided them in ascending order in Table 9 for an easier distribution visualization.

Table 9 Individual data entry referred to Figs. 10, 11, and 12

SSQ No-RGMF	SSQ Max-RGMF	SSQ Proposed-RGMF	SUS No-RGMF	SUS Max-RGMF	SUS Proposed-RGMF	Witmer No-RGMF	Witmer Max-RGMF	Witmer Proposed-RGMF
2.1	6.8	3.3	79	68.0	73.7	153	102	123
2.3	8.2	4.4	76.6	70.1	76.3	156	114	136
2.3	9.4	4.7	77.3	71.1	77.7	166	116	138
2.6	10.2	5.5	79.8	72.0	78.4	167	117	139
3.2	10.4	5.6	81.9	72.3	79.3	168	119	146
3.2	10.5	5.7	82.4	72.4	80.8	168	122	148
3.3	11.3	6	83.2	72.6	80.8	169	123	148
3.4	12.2	6.7	84.1	73.3	81.2	169	124	150
3.4	12.3	6.7	84.5	73.4	81.3	171	127	155
4.1	12.4	6.8	85.3	74.2	81.3	172	128	156
4.3	13.3	7.2	85.3	76.3	81.8	174	128	163
4.8	13.3	7.2	86.3	77.3	83.0	175	131	165
5.3	13.3	7.6	86.6	77.5	83.1	175	132	169
5.6	14.3	7.8	86.6	78.8	83.3	175	136	170
6.3	14.3	7.9	87.2	78.8	83.7	176	136	171
6.8	14.9	8.2	87.4	81.2	83.9	178	138	172
7.2	15.8	8.3	87.4	81.2	84.0	179	138	174
7.2	16.3	9.4	87.6	82.5	84.4	180	142	175
7.3	16.6	10.3	87.7	83.3	85.0	182	142	175
7.4	16.7	10.4	88.1	83.4	85.4	184	146	176
7.8	17.7	12.3	88.4	84.6	85.5	184	149	176
8.7	19.3	12.5	88.6	85.6	87.6	185	151	178
9.2	19.4	12.6	89.4	86.2	87.6	186	152	178
11	20.2	13.4	91.1	87.6	87.6	188	155	183
15.3	20.2	15	91.6	88.3	88.2	192	158	185
17.3	22.4	18.5	93.1	89.1	91.2	197	163	187

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Declarations

Conflicts of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. All information about the study and the data collected during the experiments that support the findings of this work are available from the corresponding author, M.R. Marini, upon reasonable request. The authors believe that this enhances the transparency of the presented study.

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