Evaluating Cybersickness of Walking on an Omnidirectional Treadmill in Virtual Reality

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***Abstract*—Cybersickness is a type of motion sickness that may occur during a virtual reality (VR) experience. Many studies have proposed solutions to mitigate cybersickness, while navigating a virtual environment with controllers or walking over a floor. However, reducing the levels of cybersickness while physically walking on an omnidirectional treadmill has been largely overlooked. In this article, we performed a within-subject study, where 34 novice participants underwent four visual conditions while walking in a virtual maze over an omnidirectional treadmill. In the control condition, the movement speed was reduced of the half compared to a standard navigation speed, a movement speed smoothing was added, and the user's virtual body was represented. The other three conditions changed one of the visual parameters of the control condition: in the standard speed condition, the speed reduction was not performed; for the no smoothing condition, the smoothing was not performed; and for the no avatar condition, the user's avatar was removed. Results showed that the standard speed condition was reported to induce a significant level of cybersickness compared to the control and no avatar conditions. Nevertheless, standard speed was also the condition most preferred to navigate a virtual environment. This suggests the need to find a tradeoff between the easiness to move quickly in a virtual environment and the cybersickness that can be induced. We provide a discussion of the obtained results and their implications for the design of VR experiences while users walk upon an omnidirectional treadmill.**

***Index Terms*—Cybersickness, experimental evaluation, omnidirectional treadmill, virtual reality (VR).**

I. Introduction

CYBERSICKNESS is one of the issues affecting virtual reality (VR), and relates to the experience of motion sickness symptoms like nausea, dizziness, and headache during or after VR immersion [1]. Although repeated exposure to VR can decrease the susceptibility to cybersickness [2], a bad first experience may harm a users willingness to continue using VR. Most of cybersickness research has focused on experiences in which the navigation of a virtual environment is performed either with a controller, following a predefined track, or walking over a floor within the bounds of a room [3]. However, cybersickness can also occur with other methods of VR locomotion, such as walking on an omnidirectional treadmill.

The main theory on cybersickness, the sensory conflict theory [1], addresses the source of sickness in the sensory mismatch that users are experiencing (mainly the visual-vestibular conflict). Walking on an omnidirectional treadmill might lead to a different sensory mismatch that could cause motion sickness as compared to the sensory mismatch that arises from using a conventional controller for navigating the virtual environment or walking over a floor. In the case of treadmill walking, users perceive to be visually moving forwards as they walk, but physically they are walking on the spot. Although while walking users' vestibular and proprioceptive systems perceive accelerations as well as physical and kinesthetic feedback from feet and legs, they do not receive horizontal accelerations when starting to walk or stopping. To the best of our knowledge, no study has been conducted on the assessment of the effect of different parameters of visualizing the movements in virtual environments to reduce cybersickness when using an omnidirectional treadmill. To bridge this gap, we performed an experiment, where 34 participants (all first-time users of an omnidirectional treadmill for VR applications) walked in a virtual maze under different conditions. Specifically, the study tested three cybersickness reduction methods (movement speed, movement smoothing and a virtual body representation) and their comparison against a control condition. The present work is a design-oriented study according to the categorization of Leoncini *et al.* [4], who distinguish cybersickness reduction methods in "design mitigation methods" and "neurophysiology countermeasures."

The rest of this article is organized as follows. Section II provides an overview of the main works related to our research. Section III details the conducted experiment, while Section IV reports on the achieved results. Section V discusses the obtained results. Finally, Section VI concludes this article.

II. Related Work

A. Causes of Cybersickness

The most discussed theory to explain cybersickness has been the sensory conflict theory [1], [5]. It postulates that cybersickness is induced when there is a conflict between the input of different senses. Another frequently mentioned theory is that of postural instability [6], which proposes that symptoms occur when users are experiencing postural instability and

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have not learnt yet how to stabilize themselves in that specific environment. While some authors have provided evidence for the theory [7], other authors either find postural instability as a consequence of cybersickness [8] or find no causal relation at all [9].

An additional theory that has inspired a common cybersickness reduction method is the rest-frame hypothesis [10]. It posits that cybersickness comes from the lack of finding or choosing a consistent stationary reference frame, the rest-frame, from which one can judge motions, positions, and orientations to be relative to. The hypothesis suggests that it is not the sensory conflict that directly causes cybersickness, but it is the cognitive conflict coming from not being able to find a single rest-frame that is consistent with somebody's inertial and visual motion signals.

B. Measuring Cybersickness

Most studies investigating cybersickness have used the simulator sickness questionnaire (SSQ) [11]. Although this questionnaire was originally meant for the use of simulators in the military domain (e.g., flight simulators), it is still the most established questionnaire for cybersickness in VR research. Participants rate the severity of 16 symptoms on a four-point scale from none to severe. The results are then calculated in four scores: nausea, oculomotor, disorientation, and total score.

The cybersickness questionnaire (CSQ) [12] is a subset of the SSQ. The CSQ does not have a total score, but the calculations result in two factors: dizziness and difficulty in focusing. The psychometric evaluation on the SSQ and CSQ reported in [13], revealed that the CSQ showed better validity compared to the SSQ.

A major disadvantage of the previously mentioned questionnaires is that due to their size one can only utilize them before or after a VR session. To overcome this limitation, the fast motion sickness scale (FMS) was proposed, a one-dimensional scale (that goes from 0 = no sickness, to 20 = frank sickness), which can be used while a user is in VR and correlates with the SSQ total score and nausea subscore [14].

To get objective data, it is possible to perform physiological measurements. However, there is not one specific physiological signal that is used throughout most of the studies. In the review reported in [15], the authors advocate for using electrocardiogram and blood pressure, whereas in the review presented in [1] galvanic skin response is put forward as the most reliable method of measurement. Another frequently used method of receiving real-time objective data about cybersickness is to measure the postural sway [16]. Other authors demonstrated that it is also possible to measure gait parameters to identify cybersickness [17].

One way to record postural instability is to use a balance board from which it is possible to measure the movements around the centre of gravity [18]. Another way of measuring postural sway is to gather head dispersion data. The results of study described in [19] showed that head dispersion (the change in roll and pitch), is highly correlated to the changes on the x- and y-axis around the centre of gravity. Other authors also investigated the link between the positional data from the head mounted display (HMD) and cybersickness, observing significant correlations between certain position parameters and the SSQ scores [20].

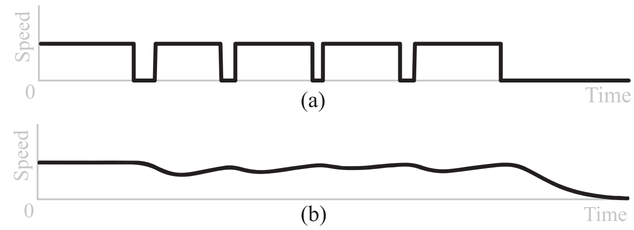


Fig. 1. (a) Stuttering steps effect on speed (b). Stuttering steps effect after smoothing.

C. Cybersickness Reduction Methods

To select the methods to adopt in our study, we performed an overview of existing cybersickness reduction methods, which is reported in Table I. This overview also consists of studies that did not involve VR, but did still concern visually induced motion sickness. Reducing the field of view (FOV), correcting the interpupillary distance and adding a rest-frame were the solutions that have been proven on the largest number of participants.

From the 14 methods shown in Table I, we selected three for our study: movement speed (at visual level), movement speed smoothing and a virtual body representation. Such methods were selected for the following reasons. First, the chosen methods are flexible in applying to different contexts, as they do not require extra hardware and do not interfere with the theme of any virtual experience. The other methods from Table I require extra hardware (e.g., head-worn haptic feedback), have to be adjusted to the specific virtual experience (e.g., rest-frame) and/or have already been tested on a large number of participants with a positive result (e.g., FOV reduction). Second, the chosen methods have not been conclusively proven on a large number of participants, and therefore we aimed at assessing their utility for our scenario of walking over an omnidirectional treadmill.

Even though visual movement speed has been shown to affect cybersickness on a fair number of participants [35], [36], some studies did not find a significant effect [37], [38]. Thus, there is value in testing it on more participants. Furthermore, by using an omnidirectional treadmill there is the chance to investigate visual-proprioceptive mismatch under a new condition. A speed that is unrealistically high might result in a visual-proprioceptive mismatch as the leg movements are not matching the visual speed.

Movement speed smoothing is a solution for which it is still unclear if it can work or not, with two studies contradicting each other [52], [53]. It is plausible to expect that it should reduce the sensory mismatch peaks, as it reduces acceleration spikes when starting and stopping. Also, smoothing compensates incorrect walking patterns of users that can cause stuttering visual steps (see Fig. 1). By reducing stuttering visual movements, the number of visual accelerations and decelerations could be lessened, which in turn would lead to fewer instances of sensory mismatch.

The third chosen method, a virtual body representation, might be able to function as a rest-frame to reduce cybersickness. Similar to the study reported in [30], which used a virtual nose,

TABLE I
OVERVIEW OF CYBERSICKNESS REDUCTION METHODS (N = NUMBER OF PARTICIPANTS)

Method	Proven	Total N	Failed to Proof	Total N
Field of view reduction	[19], [21]–[26]	284	[27]	18
Correct interpupillary distance	[28], [29]	220	-	-
Rest-frame	[30]–[34]	137	-	-
Movement speed	[35], [36]	133	[37], [38]	49
Olfactory stimulus	[39], [40]	76	-	-
Galvanic cutaneous stimulation	[41]–[44]	69	-	-
Texture complexity reduction	[45], [46]	52	[47]	25
Slow deliberate breathing	[48]	18744	-	-
Airflow	[49]	41	[50]	12
White noise	[41], [42]	39	-	-
Head-worn haptic feedback	[51]	30	-	-
Movement speed smoothing	[52]	15	[53]	24
Virtual body representation	[54]	15	-	-
Cognitive distraction	-	-	[55]	14

the whole body could be unconsciously used as reference frame. The virtual body representation has so far only been tested in a study of 15 participants [54]. The authors reported that adding a virtual body representation was effective in reducing cybersickness.

III. EXPERIMENT

The main goal of the experiment was to find out if any of the three selected cybersickness reduction methods (movement speed, movement speed smoothing, and a virtual body representation) have a significant effect on the level of cybersickness. Additionally, this experiment sought to find if other cybersickness factors exhibit themselves while using an omnidirectional treadmill with VR. A pilot test with three participants (who were not involved in the main experiment) was performed to perfect the experimental design and test the setup. The procedure, approved by the local ethics committee, was in accordance with the ethical standards of the 1964 Declaration of Helsinki.

A. Participants

A total of 39 participants were recruited, of which 34 finished the whole experiment, whereas 5 dropped out before finishing the last VR session due to a too high level of cybersickness. Regarding the participants who completed the experiment, 22 were males, 11 were females, and 1 participant did not disclose their sex. They were aged between 18 and 52 with a mean age of 29.12 and standard deviation of 8.13. Participants were sampled based on convenience through public social media posts and our personal network. They were all first-time users of an omnidirectional treadmill. Regarding previous experience with VR, 6 participants reported to have never experienced it before, 16 once, 11 two to five times, and 1 six to ten times.

B. Apparatus and Stimuli

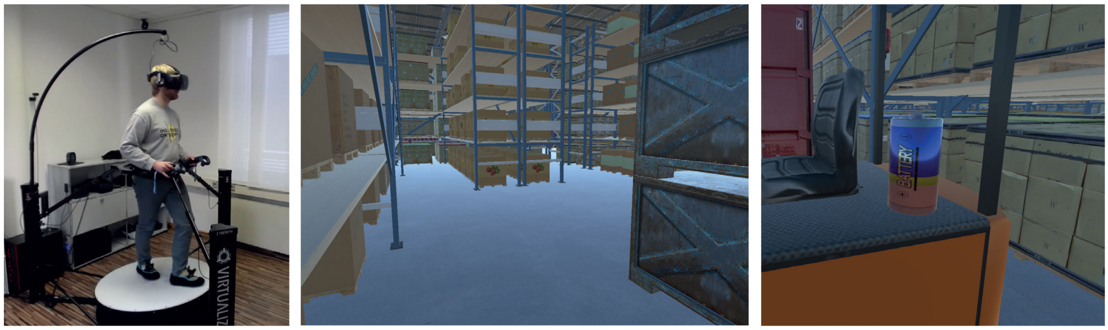
The experiments were conducted using the HTC Vive Pro VR headset and Vive controllers, with participants walking on the virtualizer ELITE 2 omnidirectional treadmill developed by Cyberith GmbH [see Fig. 2(a)]. Notably, in the virtualizer the delay between the user input (i.e., walking movements) and the scene rendered at visual level via the HMD is not perceivable. As walking on the virtualizer is a bit more exhausting than normal walking, a small and silent ventilator was always turned ON to provide some cooling for participants. The windows were also opened to have better air circulation and comply with the COVID-19 regulations.

While in VR, the participants were stuck in a warehouse maze [see Fig. 2(b)]. There was a minimap held by the right controller that started blank but was filled in as a user explored more areas [see Fig. 3(b)]. Also, we added a battery system to the minimap to make the experience more interactive and appealing to play for 32 min. The minimap had a battery life of a 100 s. If the minimap would run out of battery life, the minimap turned black with a text telling the user to pick up a battery. To keep the minimap alive, participants had to pick up batteries with one of their controllers along the way [see Fig. 2(c)]. During the experiment, when participants finished a maze, they continued with a new maze.

As for the virtual body representation, a six-point inverse kinematics system was used that was based on the unity asset Final-IK by root motion. The tracked points were the user's head (HTC Vive Pro), hands (Vive Controllers), hips (provided by the Virtualizer), and feet (Vive Trackers). The utilized model featured the same proportions as an adult human. Fig. 3 illustrates the three first-person views potentially occurring in the study: (a) view when there is no avatar associated to the user or the user's hands are not lifted, (b) view when the user's arms are lifted, (c) view when the user looks down and sees his/her body. The FPS of the experimental condition involving the inverse kinematics did not differ from that of the other conditions.

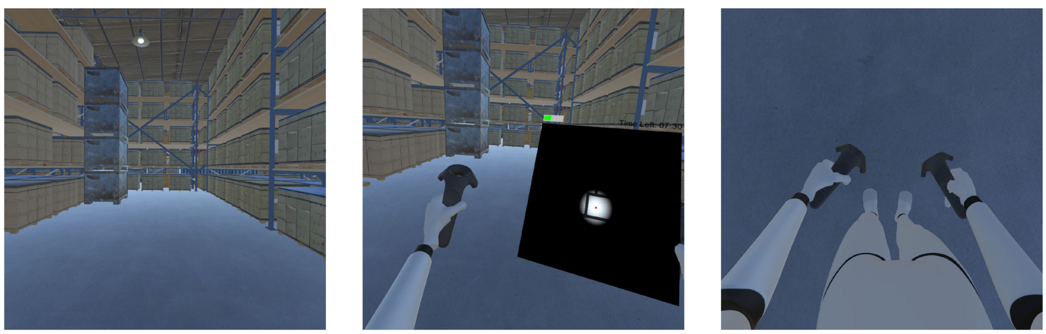
C. Procedure

Each participant underwent four sessions of 8 min, each testing a condition in which three parameters were changed:



(a) (b) (c)

Fig. 2. (a) Participant using the virtualizer omnidirectional treadmill while in VR. (b) Screenshot of the maze. (c) Screenshot of the battery.



(a) (b) (c)

Fig. 3. First-person views: (a) when there is no avatar associated to the user or the user's hands are not lifted, (b) when the user's arms are lifted, (c) when the user looks down and sees his/her body.

TABLE II
CONDITION PARAMETERS

Condition	Avatar	Speed	Smoothing
Control	Yes	Reduced	Yes
No Avatar	No	Reduced	Yes
Standard Speed	Yes	Standard	Yes
No Smoothing	Yes	Reduced	No

movement speed, movement smoothing, and virtual body representation (see Table II). In the control condition, the parameters were all set to the configuration that was hypothesized to induce the least amount of sickness. This meant a reduced movement speed factor, a movement speed smoothing factor applied, and the avatar turned ON. The other three conditions had one parameter set to what we hypothesized as more sickness-inducing: in the standard speed condition, the speed factor was doubled; for the no smoothing condition, the smoothing was not performed; and for the no avatar condition, the user's avatar was removed. By having two out of three parameters still set to a lower sickness-inducing configuration, we aimed to reduce the chance of participants dropping out due to cybersickness. Thus, instead of testing if adding a method resulted in a decrease in cybersickness, we tested if removing a method resulted in a significant change in cybersickness. To minimize the habituation effect and the cybersickness level of the previous session carrying over, conditions order was randomized and the walking sessions were separated by breaks of 10 min. During the breaks participants were asked to remove the HMD and sit on a chair.

In more detail, the movement speed and smoothing parameters were defined by a given speed factor. The visual speed of the participant was dependent on their physical walking speed and its multiplication with the speed factor. To test the effect of having a slower speed as a cybersickness reduction method, we selected a speed factor that would be in line with the physical speed of a user's legs. This was determined by adjusting the factor, so that the "standing foot" of the virtual body was not moving in relation to the virtual floor. In other words, the user was visually moving forward at the same speed as the user's feet were gliding backwards, making it seem as the virtual "standing foot" was stationary in relation to the floor. The factor that we defined for such reduced speed was half the factor that is normally used by the virtualizer software. The reason for the standard factor being twice as high as the reduced one, is to make it easier for users to traverse distances in VR.

In line with the procedures of [23], [42], [48] to minimize confounding factors, we asked participants not to drink alcohol within the 24 h before the experiment, to make sure they had a good sleep and not to have a big meal right before the test. At the start, participants were asked to fill the revised motion sickness susceptibility questionnaire (MSSQ) [56], in order to assess if motion sickness susceptibility played a significant part in the level of cybersickness of the participants. Additionally, we measured their interpupillary distance to avoid sickness

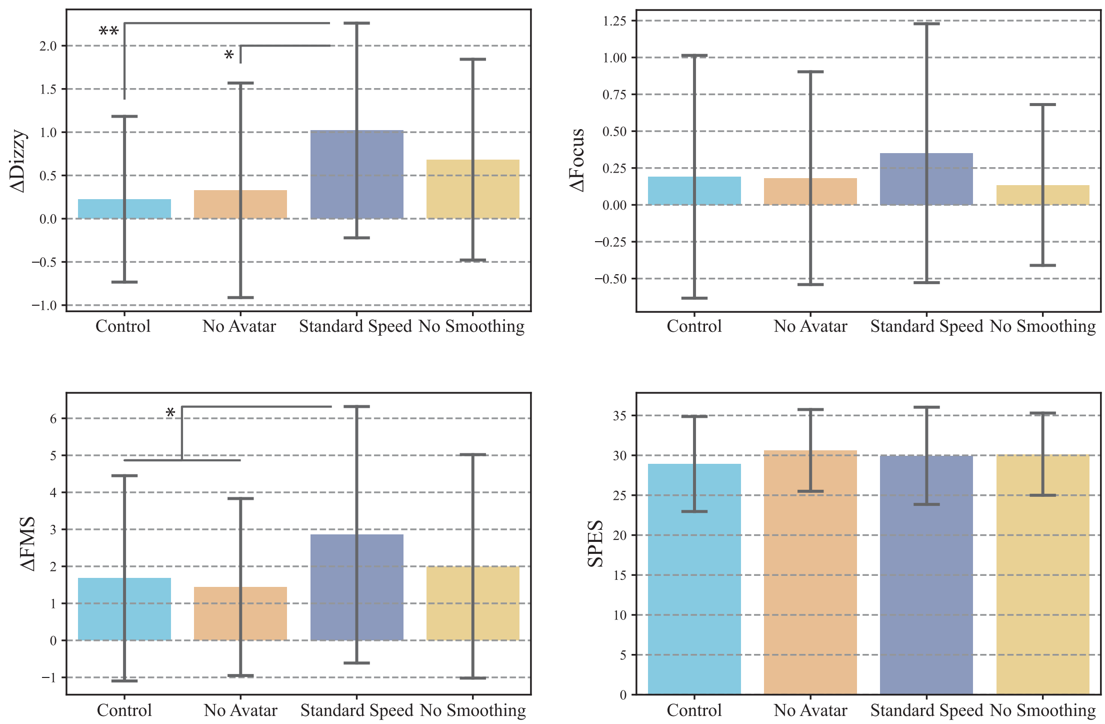


Fig. 4. Mean and the standard deviation for the ΔDizzy (top-left), ΔFocus (top-right), ΔFMS (bottom-left), and SPES (bottom-right) scores. Legend: * represents $p < 0.05$ and **$p < 0.01$.

because of nonfitting VR glasses. After that, participants were introduced to VR and the virtualizer in a short training session. In the training session, participants were instructed that they shall not run or speed walk during the experiment. This to avoid distortions and to keep the movement speed more consistent between participants and sessions. No information about the conditions was provided.

Before and after each condition, participants had to fill in the CSQ. We selected the CSQ instead of the SSQ as it was proven to show better validity [13], is comparable to SSQ in terms sensitivity (i.e., distinguishing significant differences between virtual environments with different design aspects, as also shown in [13, Table 8]) and it did not include the symptoms of fatigue and sweating. Walking on the virtualizer requires physical activity. Thus, the fatigue and sweating were likely to come from walking and not necessarily from cybersickness. In addition, after each session, participants were asked to fill in the spatial presence experience scale (SPES) [57], as we aimed to assess their level of experienced presence. Moreover, both before starting every condition and after each session, while in VR participants were requested to stand still and focus their gaze on a small red square in front of them for 30 s for a postural sway measurement. The positional (x, y, z) and rotational (pitch, yaw, roll) data of the HMD were recorded during this measurement and while participants were walking in the maze. Each maze session lasted 8 min, whereas the breaks lasted 10 min.

While in VR, participants were asked every minute their level of sickness between 0 and 20 (following the FMS method). If they reached the threshold score of 10, they were asked if they wished to discontinue the experiment. If the score reached 15, the experiment was immediately terminated. We took note of any comment made during each session. Moreover, after each session, we conducted a nonstructured interview to collect more comments for the thematic analysis, so we could better understand the participants' experience. The questions were general and open-ended about their VR and walking experience. When applicable, further enquiry was made into comments participants made during the VR session to find the reasons behind a comment. Finally, once all walking sessions were concluded, participants were asked about their preferred session and to order the sessions based on the level of sickness inducement.

IV. Results

A. *Questionnaire Results*

The results of the administered questionnaires (CSQ, FMS and SPES) are reported in Fig. 4. Regarding the CSQ, as the questionnaire was filled in before and after each session, we subtracted the scores that resulted from the presession CSQ from the scores of the postsession CSQ. The reason for the subtraction was that symptoms may persist for a longer period than the duration of the break (10 min) as reported in [2]. Thus, taking the difference between the two questionnaires filters the remaining symptoms of the previous session. Hereinafter, we refer to the two total CSQ scores as ΔDizzy (difference in dizziness) and ΔFocus (difference in difficulty to focus).

As for the analysis of FMS (where participants were asked every minute how sick they were feeling from 0 to 20), we took into account that the sessions were relatively close to each other. So, it was in principle possible for participants to still feel sick from the previous session after the break finished. Thus, we subtracted the first score of the session, the start of the first minute, from the last reported score of that session, leading to the ΔFMS score. Moreover, we included in our analysis the data of the last FMS score reported. This data is referred to as lastFMS.

An ANOVA was performed on different linear mixed effect models, one for each response variable (ΔDizzy, ΔFocus, SPES, ΔFMS, and lastFMS). Specifically, each model had the response variable and condition as fixed factors, and subject as a random factor. Post hoc tests were performed on the fitted model using pairwise comparisons adjusted with the Tukey correction. Regarding the analysis on ΔDizzy, a significant main effect was found for factor condition ($F(3, 99) = 5.32$, $p < 0.01$). The post hoc tests revealed that the standard speed condition had a higher value of ΔDizzy compared to the control ($p < 0.01$) and no avatar ($p < 0.05$) conditions. The effect sizes, computed using the Cohen's d were both medium (respectively, $d = 0.7$ and $= 0.54$).

Regarding the analysis on ΔFMS, a significant main effect was found for factor condition ($F(3, 99) = 3.57$, $p < 0.05$). The post hoc test showed that the standard speed condition had a higher value of ΔFMS compared to the control ($p < 0.05$) and no avatar conditions ($p < 0.05$). The effect sizes, computed using the Cohen's d were both small (respectively, $d = 0.36$ and $d = 0.46$). Regarding the analysis on lastFMS, a significant main effect was found for factor condition ($F(3,99) = 3.28$, $p < 0.05$). Following the post hoc test, the condition standard speed was found to have a higher value of lastFMS compared to the control ($p < 0.05$) and no avatar ($p < 0.05$) conditions. The effect sizes, computed using the Cohen's d were both small (respectively, $d = 0.34$ and $d = 0.45$).

No significant main effects were found for SPES and ΔFocus. With the same analysis method, we also investigated whether differences between conditions could occur for the subdimensions of SPES "self-location" and "possible actions," but these turned out to be nonsignificant.

Notably, whereas we randomized the order of the conditions, we were aware of the fact that "residual effects" of continuous exposure to VR could have occurred, thus causing noise in the results. To exclude the significance of any possible order effect, we computed for each participant the difference between the postexposure measurements of previous session and preexposure measurement of the current session after the 10 min breaks, for each pair of conditions (e.g., high_speed—no_smoothing, etc.). We then searched for statistically significant differences between such conditions, in the values of the CSQ, Dizzy, and Focus. For this purpose, we utilized an ANOVA performed on linear mixed effect models having the response variable (differences for Dizzy, difference for Focus) and condition pair as fixed factors, and subject as a random factor. No significant main effect was found. Therefore, it was possible to conclude that the noise was homogeneously distributed across conditions and that the analysis reported above was fully valid.

In addition, we checked for correlations between the results of the MSSQ questionnaire and the other questionnaires. For this purpose, we utilized a linear mixed effects model. The analysis showed that ΔDizzy could be predicted by the results of the MSSQ with a statistically significant relation ($\beta = 0.013$, $t(32) = 1$, $p < 0.05$). Fig. 5 shows such a correlation (MSSQ mean = 25.75, standard deviation = 23.77). All other correlations were not significant.

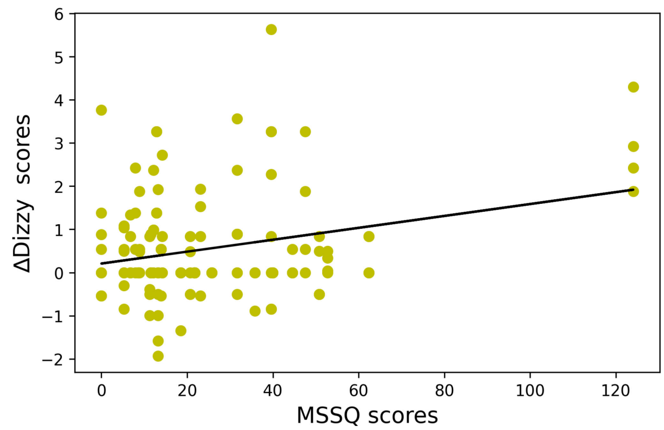


Fig. 5. Linear relation between ΔDizzy and MSSQ scores.

Furthermore, we checked if the overall motion sickness susceptibility could decrease with the time of exposure to VR, as found in previous studies [2], [58], [59]. Specifically, we tested whether there was a linear correlation between all the FMS scores and the times in which the FMS measurements were taken (for each participant 28 measurements were taken). For this purpose, we used a linear mixed effect model. Results did not indicate the presence a significant correlation.

B. *Postural Sway Measurements*

The postural sway was measured by calculating the variance of the positional (x, y, and z) and rotational data (pitch, yaw, and roll) of the HMD. For each of the six positional and rotational data, we used the difference between the measurements before and after each session (see Fig. 6). This led to the six variables ΔSway_x, ΔSway_y, ΔSway_z, ΔSway_pitch, ΔSway_yaw, ΔSway_roll.

The first 450 frames, approximately 5 s (out of 30 s), were removed to take away initial movement caused by launching the measurement. An ANOVA was performed on different linear mixed effect models, one for each response variable (three positional and three rotational HMD data). Specifically, each model had the response variable and condition as fixed factors, and subject as a random factor. No significant main effect was found.

Furthermore, we checked for correlations between the results of each questionnaire and the six positional and rotational data, in order to test the hypothesis that cybersickness leads to postural instability. For this purpose, we utilized a linear mixed effects model. The analysis showed that ΔFMS could be predicted by ΔSway_x with a statistically significant relation ($\beta = 15792$, $t(103) = 1.89$, $p < 0.05$), as well as by ΔSway_pitch ($\beta = -0.328$, $t(103) = -4.24$, $p < 0.001$) and ΔSway_yaw ($\beta = 0.16$, $t(103) = 2.37$, $p < 0.05$). Analogously, the analysis

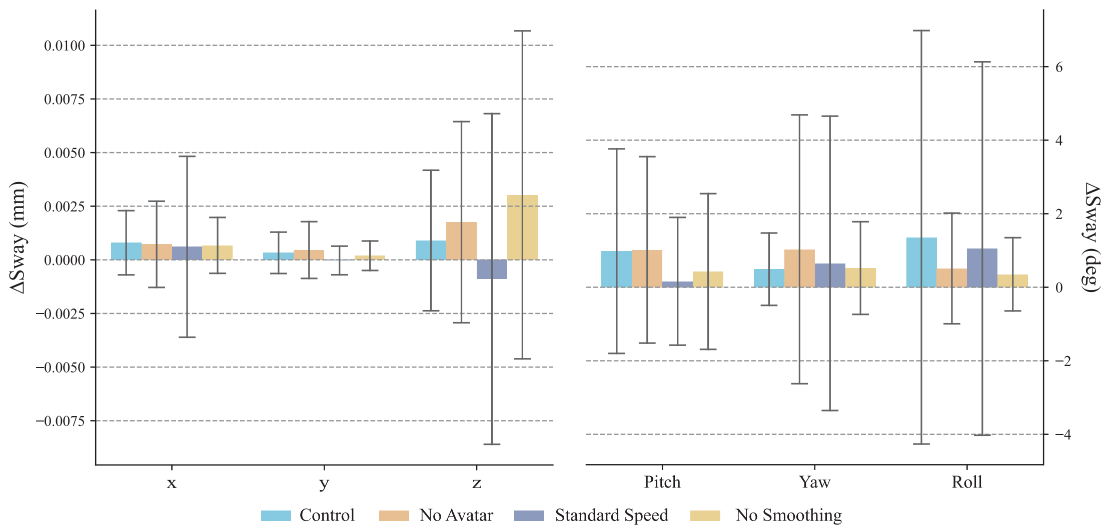


Fig. 6. Mean and the standard deviation for the ΔSway of the HMD positional and rotational parameters.

showed that lastFMS could be predicted by ΔSway_x with a statistically significant relation ($\beta = 16107$, $t(103) = 2.01$, $p < 0.05$), as well as by ΔSway_pitch ($\beta = -0.24$, $t(103) = -3.181$, $p < 0.01$), and ΔSway_yaw ($\beta = 0.14$, $t(103) = 2.21$, $p < 0.05$). All other correlations were not significant.

C. Thematic Analysis on Verbal Comments

All the verbal comments made by participants were collected in a document, which included the session, condition, and minute in which each comment was made. A total of 587 quotes was collected. Participants' comments were analyzed using an inductive thematic analysis [60]. Such analysis was conducted by generating codes, which were further organized into the following themes that reflected patterns.

Sickness. The most common topic for comments was sickness, with 142 comments. Participants discussed most often an increase in sickness when the speed factor was standard, as compared to the other conditions (e.g., *"It is the same feeling as being sick on a boat"*). On the other hand, the control and no avatar conditions saw the most comments regarding the sickness going down, precisely for 16 and 13 participants, respectively (e.g., *"When I walk slower the symptoms lessen a bit"*).

Movement Speed. The movement speed was the most talked-about parameter with a total of 108 comments. Eleven participants reported that a higher speed made them sicker (e.g., *"The faster movement feels worse"*). On the other hand, 21 participants considered the reduced speed too slow or even unrealistic (e.g., *"I had the impression I was working really hard to move and it was not letting me"*). Only one participant mentioned that the lower speed was more realistic compared to the standard speed, whereas two others did comment on the standard speed being unrealistically fast.

Turns in VR. Another aspect that caused difficulties and induced sickness was making turns in VR. The 66 comments made to this theme pointed to several causes. First, nine participants mentioned that turning while walking (without a stop) was difficult and made them feel more unstable (e.g., *"When I turn and then walk, it is much better than when I try to turn and walk around the corner at the same time. It felt better, but also less natural than what I do in the real world"*). The moving platform of the virtualizer was discussed as a destabilizing factor by seven participants (e.g., *"The rotating made it feel like on a ship as the platform was moving as well. Like a wave hit the boat"*). Six participants reported that turning too fast, made it harder or induced more sickness. Just turning the head was pinpointed by five participants as a cause of discomfort.

Unintended Speed Variations. Sixteen participants reported small unintended speed variations during walking or when stopping, mostly in the standard speed and no smoothing conditions. Such speed variations were unintended changes of the speed that were a result of unpracticed "choppy" movements of the user. Most comments were about the camera "shifting" when the user had stopped or intended to stop (e.g., *"The movement went forwards and backwards multiple times, like shaking. I felt it was then when I started feeling sick, dizzy sickness"*).

Adaptation. Many participants seemed to adapt their walking to the treadmill and learnt better how to move as the sessions progressed. Thirty-nine quotes discussed how participants either got used to VR and walking on the treadmill or adapted their walking style to be more comfortable and effective in walking (e.g., *"Big steps weren't working, so I started moving better when I did smaller steps"*).

D. Preference Analysis

When all sessions were finished, participants had to pick their most preferred session, explain their choice, and order the sessions from least sickness-inducing to most sickness-inducing. Only four participants preferred the control condition. The most preferred condition was the standard speed condition, with 14 participants [see Fig. 7(a)]. Going faster if the symptoms are not too severe was to some participants preferable over going slower and feeling less sick. Eight of those participants reported that

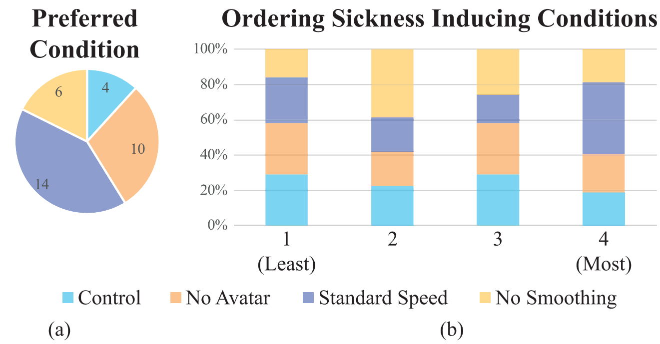


Fig. 7. Postexperiment questionnaire results. (a) Preferred condition. (b) Conditions ordered from least to most sickness inducing.

the reason for their choice was the speed (e.g., *"Best moving experience, but most nausea"*), which was deemed as more appropriate for the task of navigating the maze. An in-depth analysis at participant level revealed that those participants mostly exhibited no or mild symptoms. Conversely, two other participants mentioned the speed as the reason to choose a session with the reduced speed. One of these two participants exhibited symptoms, while the other did not.

Looking at the distribution of answers for ordering the sessions [Fig. 7(b)], participants rated the standard speed as most sickness-inducing the most often, which is in line with the results of the CSQ and FMS questionnaires. On the other hand, the difference between the conditions for the least sickness-inducing is less clear.

V. Discussion

This research sought to find out which of the three investigated methods (avatar presence, speed reduction, and smoothing application) can be utilized to reduce cybersickness for users that walk in VR with an omnidirectional treadmill. Results showed that the standard speed condition led to a significant increase in sickness scores compared to the control, as far as the questionnaire measures ΔDizzy, ΔFMS, and lastFMS were concerned. This confirms our hypothesis that reducing the movement speed factor to the level we defined can lower the reported cybersickness. The thematic analysis supports these results as the standard speed condition exhibited most comments on the sickness increasing and participants explicitly mentioned the speed as a sickness-inducing factor. Notably, we found that the level of susceptibility of participants was linearly related to the level of reported cybersickness as far as the ΔDizzy item is concerned.

The no avatar and no smoothing conditions did not reach statistical significance when compared to the control. Nevertheless, the comments about the no smoothing conditions indicate that it might have had an effect on stuttering steps and shifting. These uncontrolled speed variations might induce cybersickness. Regarding the no avatar condition, there might be a variety of reasons as to why adding or removing the avatar constituted in minor and nonsignificant differences in the cybersickness evaluations. First, it could be that virtualization of the user's own body does not provide a sufficient frame of reference that can reduce cybersickness (as we originally hypothesized). Second, it could be that the effectiveness of the avatar was reduced due to the fact that participants did not always have their arms raised. When that was the case, the avatar was not visible when looking straight forward. Third, in the no avatar condition participants could still see the in-game models of the controllers they were holding in their hands and the minimap attached to their right controller. If participants perceived the controllers and the minimap as attached to their hands and part of their movements, this might have also acted as a frame of reference object, similar to the virtual body representation, that reduced cybersickness. Our study did not manage to find a statistically significant difference between the conditions in regards to the positional and rotational variance of the HMD. In general, there was very little difference between the variance values before and after the sessions. A plausible reason for these results is that participants were kept stable by the virtualizer ring, which limited the movement of their body on the transverse plane. Therefore, there was less space for postural sway and as a consequence any head dispersion as a result of cybersickness might have been too small to measure. Nevertheless, we found correlations between some of the investigated postural sway measures and some of the CSQ responses, which indicates that cybersickness leads to postural instability, as also proven in other previous studies (see e.g., [16], [18]–[20]).

An insight retrieved from the comments was that some participants perceived the reduced speed factor as too slow and unrealistic, even though it was matching the horizontal speed of their feet sliding. One possible explanation for this is that participants might rather use the amount of effort they put in per step to predict how far each step should go, instead of taking the actual distance of each physical step. Walking on the virtualizer tends to be a bit more tiring than normal walking, thus there is more energy spent per step. This can be illustrated by the comment of one participant: *"There is a lot of energy going in, but little is coming out."* That the reduced speed feels more tiring to many users, is also confirmed by the fact that 19 out of 20 comments on tiredness were in the sessions with the reduced speed. Alongside the higher chances to successfully find the end of the maze, this might have resulted also in the standard speed condition being the most preferred condition. This is in contrast with the the results of the CSQ and FMS, for which the standard speed was deemed to be the most sickness-inducing condition. Therefore, a tradeoff seems to be necessary between the necessity to have a fast speed to better navigate the virtual environment and the risk of getting cybersickness.

The thematic analysis also showed other cybersickness factors. Most notably participants noted that turning might have also been sickness-inducing. Several participants mentioned that just rotating the head caused sickness, suggesting that the problems related to turning were, at least partly, not related to the virtualizer. The virtualizer does not affect the visual rotations, it only affects the direction of movement. There were no signs of tracking issues directly affecting the VR view. It might be that when rotating quickly, participants found it hard to focus their gaze on an object that could act as a rest-frame. The maze pathways were narrow. So, most objects that were within the visual field of the participants were close to them. Possibly these objects moved too quickly out of view, making them not usable as reference frame anymore. As participants moved quicker, it might have gotten even harder to find a rest-frame. The narrow pathways also might have forced participants to make sharper and more abrupt turns. Another possible reason why participants felt uncomfortable while turning is that it made them feel unstable. Instability causing cybersickness is in accordance with various studies that looked at postural instability and cybersickness [7], [61]–[63]. In this study, the direction of the relation between cybersickness and instability did not always seem one-way. The comment of one participant suggests that sickness also causes instability: *"The walking went well until I got dizzy."* This comment is in accordance with the study reported in [8] where authors found a negative effect of cybersickness on postural stability.

Various studies found that susceptibility to motion sickness in VR or simulators can lessen as time spent in virtual environments increases [2], [58], [59]. The present research found that in the case of the virtualizer, there are signs that improvements could already happen within the time frame of several sessions of just 8 min. Participants often mentioned that they got better at walking or felt more comfortable in VR as they got more used to it. However, the analysis on the correlation between FMS scores and the times in which the FMS measurements were taken did not turn to be statistically significant.

Taken together our results have implications for the design of VR experiences while users walk upon an omnidirectional treadmill. The findings show that the movement speed can influence the reported cybersickness. On the other hand, the comments demonstrate that in general participants preferred to move through the virtual environment quickly. Therefore, it would be beneficial to the user to have the possibility to select the appropriate movement speed before the VR experience or even change it in real-time during the VR experience. A dedicated system could be designed for this purpose. Furthermore, VR experiences could be accommodated to slower speeds by reducing the travel distances in the virtual environment, which could lower the impact of a reduced movement speed on travel time and enjoyment. Last, when new users are introduced to walking in VR over an omnidirectional treadmill, the habituation effect could be taken into account. Instead of keeping speed or smoothing at a constant value, it could be continuously set at a level that possibly induces the least amount of cybersickness. As they get more used to it, the speed and smoothing factors could be adjusted.

Notably, our study has some limitations. First, a sizeable portion of the participants did not get sick at all or only very little. This meant that for them the conditions did not have a significant effect on their level of cybersickness. Thus, a part of the sample size consists of participants that did not show any distinguishable result. Second, our study involved only one kind of virtual environment, i.e., a virtual maze. Although our findings clearly indicate differences between the experimental conditions, the generalization of the reported results to other kinds of virtual environments remains to be assessed.

VI. Conclusion

The primary goal of this study was to investigate how cybersickness could be reduced for users of an omnidirectional treadmill when in a VR experience. For this purpose, we compared three parameters (movement speed reduction, movement smoothing, and a virtual body representation) during the task of walking through a virtual maze. Results of the questionnaires showed that on average participants reported to get significantly more sick compared to the control condition when the movement speed was set to the standard factor. The other two conditions did not lead to significant differences in reported cybersickness compared to the control. These results deriving from the questionnaires were not confirmed by the head dispersion data from the HMD, but this might be due to the fact that the utilized omnidirectional treadmill is equipped with a ring that keeps the participants stable. Nevertheless, the thematic analysis on the verbal comments of the participants confirmed the results of the questionnaires.

Whereas results showed that the standard speed condition was reported to induce a significant level of cybersickness compared to the control condition, standard speed was also the condition most preferred to navigate a virtual environment. This suggests the need to select a speed appropriate for each user, which is able to find a tradeoff between the easiness to move quickly in a virtual environment and the cybersickness that can be induced. It is worth noticing that the utilized treadmill is based on the sliding of the feet onto the platform, which allows users to move in a way that is close to actual walking although not the same. Nevertheless, the conclusions drawn in this article can potentially be applied to the development of future treadmills able to realize a move closer to that of actual walking. Indeed, it is plausible to assume that walking actions similar to the ones accomplished with the utilized tread-mill would lead to similar cybersickness levels under the various conditions tested in the present study.

Various studies have provided evidence that real walking is the optimal interaction technique for navigation of virtual environments since it produces a higher sense of immersion, increases naturalness, and improves task performance compared to other solutions [64]–[66]. Omni-directional treadmills are one of the most promising systems for navigating virtual environments as they have the benefit of providing realistic walking conditions and at the same time, they allow to overcome the intrinsic spatial limits of walking in a conventional space such as a room, which is typically much smaller than the space of the virtual world. Therefore, investigating cybersickness issues resulting from the interaction with an omnidirectional treadmill is important to advance the design of this kind of locomotion interfaces.

There are various avenues for future works. In the first place, we plan to test again the effect of a virtual body representation on cybersickness with an improved experimental setup, where the avatar can be made visible more often. A first step in this direction could be to utilize a VR device that has a higher vertical FOV than the one used for our experiment. A higher vertical FOV would increase the chance that the hands and arms are within the visual field of the participants. Another way to increase the visibility of the arms would be to set up a user task that forces or stimulates participants to lift their hands. Furthermore, future experiments should remove any in-game models that are attached to the body or the controllers that could act as a reference point for users. Another approach could be to utilize reference objects, such as a crosshair at the center of viewport, or a virtual motorcycle helmet like framing around the users viewport (if it is convenient with the narrative).

We also plan to measure gait parameters by means of feet trackers similar to the work described in [17]. If certain motion characteristics can be successfully related to cybersickness, an early warning system or a closed-loop system, like the one reported in [67] could be developed. Such a monitoring system could help operators to continuously keep track of the level of cybersickness of users, without having to ask them constantly and pulling the user's attention to the sickness. Nevertheless, we are aware that solutions like those reported in [17] and [67] might be challenging for treadmills like virtualizer, if the ring of the hardware prevents taking clean measurements of sway as we hypothesized for the present study

The user study has shown that some participants did not perceive the reduced speed to be realistic and optimal to quickly navigate the virtual environment. We hypothesized that users related their muscle effort to how fast they expected to move. A new study could test this hypothesis by performing an experiment in which the physical effort required for walking and the VR speed can be adjusted. Finding the mechanisms of the visual-proprioceptive mismatch could support further development in making walking in VR over an omnidirectional treadmill less prone to cybersickness and more realistic, and as a consequence improve immersion.

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