Tiles to Move: Investigating Tile-Based Locomotion for Virtual Reality

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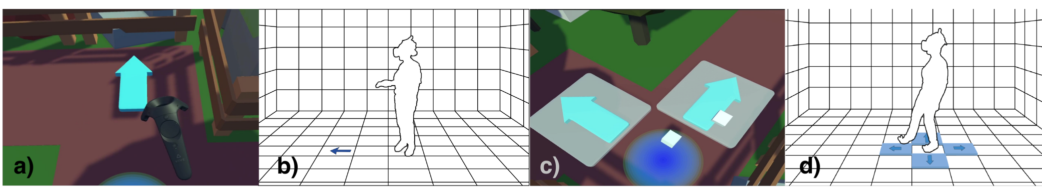

Fig. 1. The figure shows both TBL techniques. (a) The in-game perspective for the *TB-Controller*; the blue arrow indicates the direction the participant is looking, and the movement will be executed. (b) The outer perspective of *TB-Controller*. (c) The in-game perspective of a user on the virtual DancePad while using a *TB-Feet*. (d) The outside view of *TB-Feet* with the layout of the four directions.

Tile-based locomotion (TBL) is a popular locomotion technique for computer, console, and board games. However, despite its simplicity and unconventional movement, the transfer of TBL to virtual reality (VR) as a game platform remains unexplored. To fill this gap, we introduce TBL for VR on the example of two techniques: a controller and a feet-based one. In a first user study, we evaluated the usability and acceptance of the techniques compared to teleportation and touchpad locomotion. In a second exploratory user study, we evaluated the user experience of both TBL techniques in a maze and a museum scenario. The findings show that both techniques provide enjoyment and acceptable usability by creating either a relaxing (controller-based) or a physically active (feet-based) solution. Finally, our results highlight that TBL techniques work particularly well for small, constrained spaces that allow users to focus on exploring details in the nearby environment (important for games) in contrast to large open spaces that require faster locomotion, like teleportation.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**;

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1 INTRODUCTION

For decades, grid or tile-based locomotion (TBL) has been used to navigate worlds in a variety of game types (e.g., Boardgames[1], Crypt of the Necrodancer [24]). The simplicity of TBL seems to be a driving factor for its popularity and might explain why games using TBL are still experiencing high popularity today. However, to our knowledge, the application of tile-based techniques in virtual reality (VR) has not been explored yet. We believe that VR games are missing out on a promising opportunity to enable new experiences (e.g., new movement patterns, simple rhythmic movements) and challenges (e.g., limited step size, restricted directions) for VR applications and games. Furthermore, TBL could address some limitations in existing locomotion techniques, such as cybersickness through step-based interaction or precision through selecting tiles instead of granular positions. Moreover, commonly used locomotion techniques like teleportation can negatively impact immersion through unnatural big jumps [49, 52]. Also, it could cause users to miss environmental details on the way by "jumping" past. Another well-known locomotion technique uses controllers for moving (i.e., joystick/track-pad sliding). However, it is known to cause cybersickness [22, 34]. Additionally, controller usage limits physical activity compared to real-world movement, and we know that even standing and doing small movements can contribute to improved engagement, enjoyment, and motivation [46].

Inspired by the research gap of TBL in VR, we designed and implemented two TBL techniques: *TB-Controller* and *TB-Feet*. Using tiles as an underlying floor division, where you can move one unit in each direction, we aim to keep simplicity for designers and users. Meanwhile, we expect the novelty and challenge these techniques provide will contribute to users' enjoyment. In contrast to locomotion techniques like teleportation, these TBL techniques limit the fast interaction range (e.g., jumping from one location to another) and thus create time to focus on details along the way. Further, we suspect that the step-like non-continuous design of the techniques will keep cybersickness low [22, 34] compared to joystick or sliding and gliding movements. We chose to implement two types of TBL that integrate different levels of physical activity.:

(1) With *TB-Controller*, we implemented the movement using an HTC Vive controller track-pad. Here, users move by selecting a tile next to them by touch input on the controller track-pad.
(2) With *TB-Feet*, players move through pressing virtual buttons on the ground with their feet (using feet tracker) facing the desired direction in VR (like on a dancepad [43]).

We evaluated our TBL techniques in two user studies. The first study (N=30) quantitatively compared the effects of (1) *TB-Controller* and (2) *TB-Feet* with the commonly used locomotion techniques (3) *Teleportation (TP)* and (4) *Sliding Movement* on the following dependent variables: cybersickness, usability, presence, enjoyment, heart rate, aim precision, and speed. The second study (N=16) was an exploratory one, where we demonstrated the applicability of our TBL techniques in two scenarios: a game and a learning experience implemented as (a) a maze and (b) a museum, respectively. We collected qualitative feedback from eight participants on the participants' user experience, perceived advantages/disadvantages, and exhaustion level.

[1]https://www.youtube.com/watch?v=9bn9uos9XFc

Our studies show that the TBL techniques do not cause noticeable cybersickness, are enjoyed by participants, and enable equally precise positioning. In the first study, we only find significant differences between *Teleportation* and all other locomotion techniques regarding interest/enjoyment. However, our qualitative analysis in the second study provided insights that enjoyment of the TBL techniques depends on the task and environment (distracting and detailed), while for *TB-Feet*, the motivation to be physically active plays a big role. Regarding usability for the first study task, both TBL techniques are around the considered average of systems between "ok" and "good" [3]. Nevertheless, the speed of both TBL is significantly slower compared to *Teleportation*, where *TB-Controller* is the closest to *Teleportation*.

The results of our second study suggest that both *TB-Controller* and *TB-Feet* were perceived as easy to use and less likely to run against physical objects than simply walking in VR. Further, TBL seems to be more fitting for specific scenarios (e.g., maze), where people have to focus on details that are nearby in a tight space and are more distracted through a demanding task. For *TB-Feet*, aligning with quantitative results, some participants commented about the physical demand of the technique (e.g., exhausting or requiring balance). Overall, our results show that TBL techniques are enjoyable and have great potential as a game mechanic or locomotion technique in detailed and distracting VR games or applications.

In summary, our work makes the following contributions:

(1) We introduce TBL for VR and design and implement two locomotion techniques: *TB-Controller* and *TB-Feet*.
(2) We compare the effects of these two techniques with common locomotion techniques and find that they perform well in cybersickness, enjoyment, and usability. In terms of aiming, TBL performs very precisely, while for *TB-Feet*, the heart rate is highest.
(3) We demonstrate the applicability of these techniques to other VR applications in a second qualitative user study.
(4) Finally, we discuss implications for future work on using TBL techniques.

2 RELATED WORK

Locomotion in VR is a widely researched topic, as demonstrated by a literature review from 2021 by Di Luca et al. [18], who identified more than 100 different types of locomotion techniques. Although, a lot of locomotion techniques have been explored, the literature still reports its various challenges, for example, unlimited VR and limited real-world space, presence, cybersickness and costly hardware.

2.1 Effects of Locomotion Techniques and their Use Case Scenarios in Virtual Reality

VR Locomotion research focuses on tackling several challenges [8, 39], but also tries to explore new possibilities by pushing boundaries [16, 59]. Hence, many researchers try to answer if there will be a "best" unified locomotion technique. Di Luca et al. [18] promotes *"Perhaps, this exploration will never end, as different locomotion techniques might be more tailored to specific tasks, so no single locomotion technique will ever fully satisfy all constraints"*. Yet, some characteristics are always crucial for creating a decent VR experience, such as avoiding cybersickness [17, 41]. Another challenge is avoiding bulky or costly additional hardware [20, 27, 29, 31], as it is not accessible by everyone.

Furthermore, there is evidence that some locomotion techniques provide higher presence. While [58] have small indications that controller movement (*Sliding*) creates higher presence, Clifton and Palmisano [14] found that controller movement (*Sliding*) actually creates higher presence over time compared to *Teleportation* and that the effect is stronger for women. Further, compared to *Teleportation*, *Sliding* was found to be easier to use [8]. However, Kim et al. [33] found that

Teleportation is faster than walk or run-in-place and *Sliding* but had the highest error time ratio, and walk-in-place locomotion seems to be riskier in terms of safety compared to *Teleportation*. Moreover, step-based techniques matching human body walking movements like walk-in-place locomotion provide higher presence than pointing techniques like *Teleportation* [52], as well as natural walking in VR [45, 49]. Using the feet for moving can even reduce cognitive load [61] and redirected walking that includes physical movement performs highest in special knowledge [34] compared to *Sliding* and *Teleportation*. These findings lead us to consider exploring physical active, step-based locomotion alternatives for VR.

Regarding use case scenarios, free *Teleportation* created the slightest discomfort and highest enjoyment compared to *Sliding* (touchpad-based, controller movement and human joystick) while moving through an open Zoo environment (Frommel et al. [22]) or an open village environment (Vlahović et al. [58]). Further studies by Clifton and Palmisano [14], Langbehn et al. [34] also confirmed that *Teleportation* leads to less cybersickness than *Sliding* [14, 34]. Nevertheless, there is little research on how use-case scenarios might be important for specific locomotion techniques.

2.2 Tile-Based Locomotion

TBL is implemented in a wide range of PC games [6, 57], but most research on tile-based games focuses on path-finding algorithms [2] rather than evaluating user experience. Therefore, there is a research gap in understanding the effects, benefits, and disadvantages of TBL on user experience.

The lack of TBL also applies to VR. We only found one locomotion technique for VR called Cloudstep in the Locomotionvault[2], which is close to TBL without having a fixed grid. It uses the trackpad to create a step-like experience and provides a step-length teleport into the desired direction angle on the touchpad to move toward the direction giving 360° of freedom for doing "steps". However, to our knowledge, there is no evaluation of this technique. Interestingly, a recent paper [15] used tapping and jumping patterns on a tile-based exergame to provide lower body training in VR; however, they did not use these tapping movements for locomotion.

2.3 Physical Activity

Many research reports the risks of sedentary behavior. While there are physical risks [54], we further find negative impact on happiness [35] and mental health [44, 48, 55].

While some are skeptical if exercise games (Exergames) reach the level for health benefits [30, 38], research shows that even little activity can be benefiting [13, 25, 29]. Benatti and Ried-Larsen [5] showed that breaking up prolonged sitting time can already positively affect health with "light-intensity ambulatory physical activity". Dunstan et al. [19] reported that even physical active people who have prolonged unbroken sitting time can risk their health.

While many VR games are focused on exercise aspect [7, 15, 28, 29], we can also find locomotion techniques that incorporate small to high physical activity [33, 59]. Whole-body movement in VR was found to be engaging and enjoyable when the motivation for in-cooperating whole-body movement into locomotion is given [26]. Further, Rogers et al. [46] argued that whole-body movements do not always have to be realistic to create a physical challenge, contributing to engagement and enjoyment.

2.3.1 DancePad. A physical active, step-like locomotion technique could be a DancePad [43]. A few studies investigated dance pads as a locomotion or interaction technique, but all had low sample sizes, and none of them used immersive VR (i.e., head-mounted displays) [4, 37, 50, 51].

In a study by Fassbender and Richards [21], they used a DancePad as hardware to navigate through a virtual open space; the results revealed hardware problems like lagging in response time.

[2]https://locomotionvault.github.io

Participants were stepping off the DancePad because of vertigo and balance issues and reported the locomotion technique not being intuitive. However, a study of Masek et al. [40] found DancePads as enjoyable and motivating while raising the heart rate in a jump-and-run game on a screen.

As DancePads are suitable for tile-based movement and gain benefits through (even small) physical activity, we decided to implement not only a TBL for the controller but also one for the feet. Additionally, hands-free movement can decrease cognitive load and increase efficiency [36].

A study by Xu et al. [60] investigated a DancePad interface (DMove) for AR with 8 or 16 tiles around the user that can be used for remote control of, for example, devices in the environment or for dance Exergames. They found that their posture recognition method is very accurate, DMove has equal task completion time to a Hand and Hand-Head Method, and low workload, but high usability and novelty.

3 TILE-BASED LOCOMOTION

We designed two TBL techniques for VR: one controller-based (i.e., *TB-Controller*: see Figure 1a,b) and one feet-based (i.e., *TB-Feet*: see Figure 1c,d). In the following, we describe the concept of the techniques and provide details about their implementation.

3.1 Grid System

Both locomotion techniques need an underlying grid system on the movement plane. We made the movement possible by repositioning to the next tile of the grid. Depending on the scenario, the grid does not have to be visible like in our case. Both locomotion techniques are limited to four directions, like on a DancePad [43], excluding diagonal movement for simplicity. Furthermore, we wanted to avoid too many small areas on the controller trackpad, and for comparability, we needed both techniques to have the same movement possibilities.

3.2 Tile-Based Controller

The *TB-Controller* technique uses the controller for movement. The four directions can be chosen using the controller's trackpad (see Figure 2 the grey circle). The trackpad itself is separated into four pieces with angles of 90°. Each of the four angles represents the tile next to the player in that direction overlayed as the black squares in Figure 2. When the user wants to move on a tile, the represented angle in the direction on the touchpad has to be pressed (e.g., for the tile on the left (x-1,y), the finger has to press in the left trackpad area). The orientation of the trackpad is mapped to the viewing direction of the head, and therefore, it can be changed by looking in another direction. We chose the viewing direction since gaze indicates where a person wants to go. This approach has been also used in previous work [56, 59]. An arrow on the ground visualizes the user's viewing direction (see Figure 1). The four directions on the trackpad change orientation depending on the viewing direction. Consequently, users cannot only move forward, sideways, and backward by pressing the desired direction on the trackpad but can only press forward and change the viewing direction to move in all four directions. Based on Martinez et al. [39]'s work, we categorize *TB-Controller* as a combination of *Head-directed Steering* and *Look-and-Motion* technique of Selection-based Locomotion where the four tiles around the participants are the only possibilities for selection in our implementation.

3.3 Tile-Based Feet

The *TB-Feet* technique uses HTC Vive trackers on top of both front feet for locomotion. The trackers are represented as white cubes in Figure 1c). The tile the user stands on is surrounded by four arrows on the ground facing the four tiles or directions the player can move. To move in the desired direction, one foot (illustrated as a white cube) has to be put onto the ground arrow that is facing

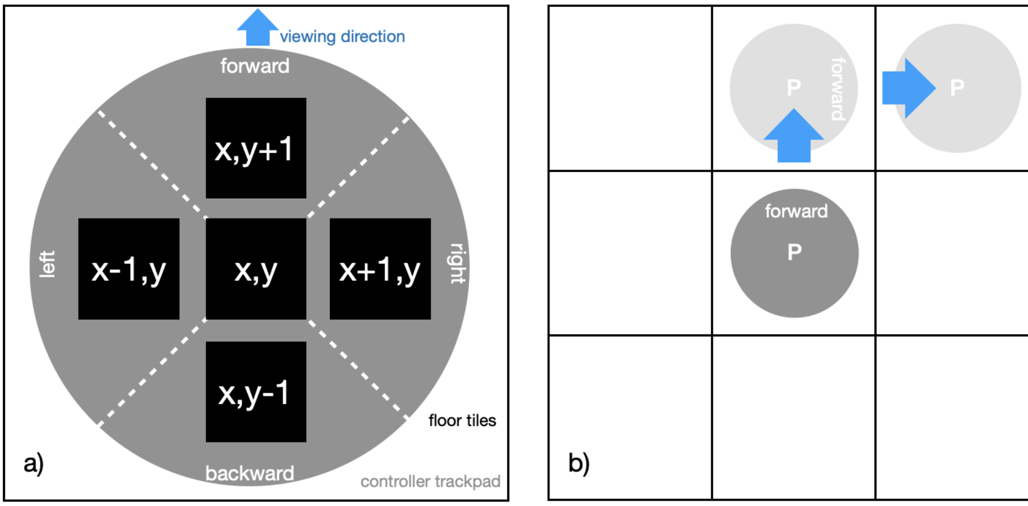

Fig. 2. a) The figure combines both locomotion techniques and its underlying logic. The black part shows the floor tiles, where x,y is the current position, from where the four directions can be chosen. For *TB-Feet*, the direction is chosen by tapping with the foot on a virtual button of the four directions (x,y+1;...). For moving with *TB-Controller*, the grey area shows the touchpad of the HTC Vive controller, where the four areas are split. The movement will be executed on the black tiles depending on the area the finger clicks. Here, the viewing direction (blue arrow) is important because changing the viewing direction will rotate only the touchpad to the new direction but not the tiles. We wanted to keep forward always in the viewing direction, even if the player was turning and facing a different direction. b) The birds-eye view shows how the participant would move forward if the viewing direction is changed and the forward button is pressed. It would be possible as well to further view forward but press the right button for moving to the right.

the desired direction. Releasing the foot will move the user on the tile in the chosen direction. According to Martinez et al. [39], we would categorize *TB-Feet* in Partial-Gait Locomotion.

4 USER STUDY 1: COMPARING THE TBL TECHNIQUES WITH *TELEPORTATION* AND *SLIDING*

To investigate how our two TBL techniques perform on an obstacle-free open area in comparison to other established locomotion methods regarding cybersickness, interest/enjoyment, usability, presence, and exhaustion, we designed a within-participants user study. The primary aim of our study is to investigate the feasibility and acceptance of our techniques compared to the two well-known and standard implemented techniques in, for example, the SteamVR Unity Plugin[3] but also many VR games and research [39]. These two locomotion techniques are *Teleportation* as Point-and-Teleport[4] and Sliding[5] (also known as joystick-directed steering technique). This study answered the following research question:

RQ1: *How do* TB-Controller *and* TB-Feet *locomotion perform concerning cybersickness, enjoyment, usability, heart rate, speed, and precision compared to the widely known* Teleportation *and* Sliding *techniques?*

[3]https://valvesoftware.github.io/steamvr_unity_plugin/articles/intro.html
[4]https://www.youtube.com/watch?v=ebduy3C5pzA
[5]https://www.youtube.com/watch?v=Qg72xxgsOfE&feature=youtu.be&t=93

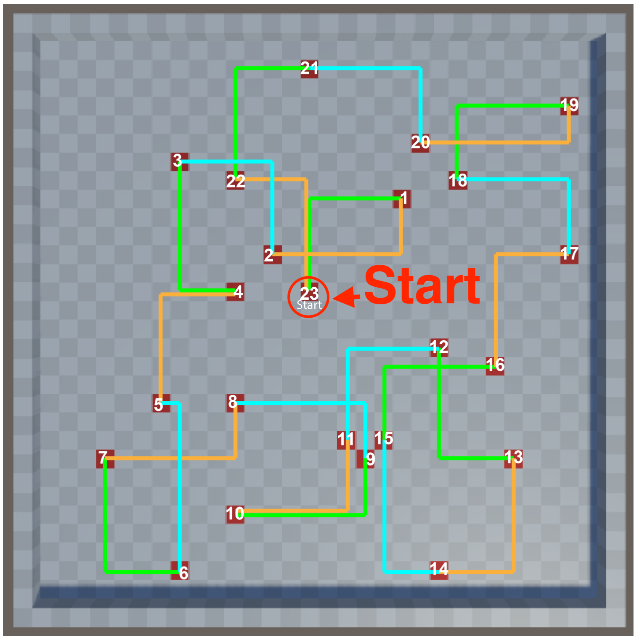

Fig. 3. The lines show the shortest path from one red tile to the next one. Each tile has a number that appears in the same order after the previous number is reached by stepping in it. Twenty-three tiles will appear, and tile 23 is the starting point and the last tile.

4.1 Study Design

In our within-participants study, each participant completed four conditions. Each condition used the same setup. Starting from the red tile (number 23), participants had to move to the next red tile that was visible on the plane. The red tiles appeared in the order of the numbers in Figure 3. After a red tile was reached, the next red tile appeared. The area was an empty open space except for one visible red tile.

4.1.1 Conditions. The study consisted of four experimental conditions. To avoid learning effects, the conditions were counterbalanced with a Latin Square.

(1) ***TB-Controller*** **(TBC):** In this condition, the players used the *TB-Controller* method (see subsection 3.2) to reach the next red tile.
(2) ***TB-Feet*** **(TBF):** In this condition, the players used the *TB-Feet* method (see subsection 3.3) to reach the next red tile.
(3) ***Teleportation*** **(TP):** In this condition, the players moved using teleportation. This method uses a controller with a virtual pointer. Through this pointer, you can select a spot to move at directly without having to travel to it.
(4) ***Sliding Movement*** **(SLI):** In this condition, the players used the trackpad for continuous sliding movement above the ground in the direction of the next red tile. The sliding stops when the finger is lifted from the trackpad and continues when touching the trackpad again in the direction of the finger on the trackpad.

4.1.2 Measures. We used in-game metrics as well as questionnaires to assess users' experience. Additionally, we collected the following demographics: age, gender, VR experience, and physical activity level.

In-Game Metrics. During each condition, we recorded participants' average and maximum heart rates through a smartwatch. Furthermore, in-game performance data was logged: timestamps of reaching a red goal tile, the aiming precision (i.e., the distance in unity between the position where the participant landed on the goal tile and the middle point of the goal tile), number, and time of reached goals. Moreover, the study conductor documented additional observations.

Questionnaires. We used standardized questionnaires to measure cybersickness, enjoyment, usability scores, and presence of the participants.

Cybersickness: To compare the (potentially participant different) previous state before any condition happened and past each condition state, participants answered all questions of the Simulator Sickness Questionnaire (SSQ) [32] at the beginning of the study and after each condition on a 4-point scale (0/none - 3/severe). The questionnaire consists of 16 items that allow for a calculation of total SSQ (TS), nausea (N), oculomotor disturbance (0), and disorientation (D) category scores.

Interest/Enjoyment: We used the intrinsic motivation inventory (IMI) [47] to obtain interest/ enjoyment scores (7-point scale from 1="not at all true" to 7="very true")).

Usability: The System Usability Scale (SUS) [12] was used to collect usability ratings of participants (5-point Likert scale from 1="Strongly disagree" to 5="Strongly agree"). A score of > 70 indicates good usability [3].

Presence: Presence was measured using the Slater-Usoh-Seed Questionnaire (SUS) (7-point Scale from answers where 1 is not very present to 7 very much present), as it being short and most used according to Martinez et al. [39].

Aiming Precision: A single item custom question asked participants: "Aiming for the red field was ..." with a 7-point scale from 1="Very easy" to 7="Very hard".

4.1.3 Participants. We recruited 30 participants (10 female, 20 male, M_{age} = 25.63, SD = 3.41, Min-Max= 19–33). 80% of the participants were university students, and 70% had a computer science background. 83.33% had used a VR headset before, but only 13.33% of the participants owned a VR headset. 40% of the people who used VR normally move with teleportation, 30% use sliding, and the rest used walking or applications with no movement.

4.1.4 Procedure. The participants first signed the informed consent and then started by filling out the initial SSQ questionnaire. Afterward, for each condition, an introduction guided them through the process and the locomotion techniques they had to use. During the conditions, the players were asked to reach as many of the red tile targets as possible, appearing in the numbered order in sequence. The duration of each condition was limited to two minutes. Following each condition, they filled out the post-game questionnaires. After all four conditions were finished, each participant was asked about their demographics, VR experience, and physical activity level. The volunteers were given 10 Euros as remuneration.

4.2 Quantitative Findings

We checked the assumption of normality using Shapiro-Wilk tests. Based on their results, we either conducted Friedman (non-parametric) or Repeated Measures ANOVA (parametric) tests to evaluate the differences between the four conditions on the dependent measures. For the post-hoc tests, we performed Bonferroni correction. We report significant post-hoc results with this correction. Table 1 shows descriptive values, as well as statistical test results of the quantitative measures.

Table 1. Mean values (M) and standard deviation (SD) for all significant measures. Further, Friedmans ANOVA (fA) for non-parametric and repeated measures ANOVA (A) for parametric results, effect size Kendall's w or η^2, and post-hoc results for significant conditions are reported using Bonferroni correction. SSQDivTS is the difference between the pre-study and post-condition overall SSQ value.

Conditions	SSQDivTS		Int/Enj (IMI)		Usability (SUS)		Heart Rate		Aiming Precision		Time Between Goals	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
(1) TBC	-0.12	19.65	4.30	1.29	64.25	16.75	85.56	11.62	0	0	7.67	2.01
(2) TBF	0.37	21.86	4.38	1.16	61.91	12.17	96.26	12.52	0	0	1.32	6.76
(3) TP	-3.24	18.34	5.51	1.06	87.08	10.04	87.66	12.27	1.63	0.10	4.00	1.43
(4) SLI	16.58	30.79	3.83	1.30	65.50	15.97	84.36	11.82	0.25	0.02	9.84	1.68
Statistics	Test	Effect	Test	Effect	Test	Effect	Test	Effect	Test	Effect	Test	Effect
$\chi^2(3)$ *p* value	fA = 13.2 p < .01	w = 0.146	A = 10.5 p < .0001	η^2 = 0.213	A = 20.9 p < .0001	η^2 = 0.351	A = 5.95 p < 0.001	η^2 = 0.133	fA = 90 p < .0001	w = 1	fA = 67.6 p < .0001	w = 0.751
Post-hoc	Cond.	p_{adj}	Cond.	p_{adj}	Cond.	p_{adj}	Cond.	p_{adj}	Cond.	p_{adj}	Cond.	p_{adj}
	SLI ↔ *TP*	< .01	*TP* ↔ *SLI*	< 0.001	*TP* ↔ *SLI*	< .0001	*TBF* ↔ *SLI*	< 0.01	*SLI* ↔ *TBC*	< .0001	*TBC* ↔ *TBF*	< .0001
	SLI ↔ *TBC*	< .05	*TP* ↔ *TBF*	< 0.01	*TP* ↔ *TBC*	< .0001			*SLI* ↔ *TBF*	< .0001	*TBC* ↔ *TP*	< .0001
	SLI ↔ *TBF*	< .03	*TP* ↔ *TBC*	< 0.02	*TP* ↔ *TBF*	< .0001			*SLI* ↔ *TP*	< .0001	*TBC* ↔ *SLI*	< .0001
									TBC ↔ *TP*	< .0001	*TBF* ↔ *TP*	< .0001
									TBF ↔ *TP*	< .0001	*TP* ↔ *SLI*	< .0001
											TBF ↔ *SLI*	< .05

The results of cybersickness show significantly better scores for all locomotion techniques against *Sliding*. In the given scenario with the given task, participants enjoyed *Teleportation* significantly more than all other conditions and also thought that *Teleportation* was significantly better in usability.

In terms of physical activity, the findings show a significant effect between the conditions *TB-Feet* and *Sliding*. While *TB-Controller* and *Teleportation* do not create a significantly lower heart rate, we still see tendencies towards it. There was a significant effect of the conditions on heart rate values after controlling the effect of age as a covariant [42], F(1,115)=8.37, p<.0001. We further measured presence but did not find any significant results (*TB-Controller*: M = 3.17, SD = 1.39; *TB-Feet*: M = 3.16, SD = 1.29; *Teleportation*: M = 3.40, SD = 1.11; *Sliding*: M = 3.43, SD = 1.12) The precision for TBL techniques is zero because the implementation of tile selection positions the player exactly in the middle of the chosen target. The two TBL techniques (*TB-Feet* and *TB-Controller*) are significantly more precise compared to *Teleportation* or *Sliding* in meeting the exact center of the target due to their implementation. Thus, we cannot make a statement about comparing them to the *Sliding* and *Teleportation* techniques. However, we can see that targeting the middle point with *Sliding* is a lot closer to 0 than with *Teleportation.* Further, we can see in Figure 4 that this aligns with the perception of participants. In the custom question, all locomotion techniques were rated significantly easier to aim for the target than *Teleportation* (*TB-Controller*: M = 3.66, SD = 1.47; *TB-Feet*: M = 3.83, SD = 1.34; *Teleportation*: M = 1.76, SD = 1.13; *Sliding*: M = 3.63, SD = 1.29, fA = 45.0, p<.0001, post-hoc: *Teleportation* against *Sliding* p_{adj}<.0001,*TB-Controller* p_{adj}<.0001,*TB-Feet* p_{adj}<.0001). There was also a significant effect of condition on the time measurement between goals; *Teleportation* led to the fastest completion time between goals than all other conditions, while *TB-Feet* had the slowest. All conditions were significant to each other, which suggests that the time between goals is very fixed for each locomotion technique. More distributions as boxplots can be seen in Figure 4.

5 USER STUDY 2: EXPLORATION OF *TB-CONTROLLER* AND *TB-FEET* IN TWO SCENARIOS

To see the applicability of TBL techniques to different scenarios, we conducted an explorative study and qualitatively evaluated participants' experiences. After focusing on characteristics between

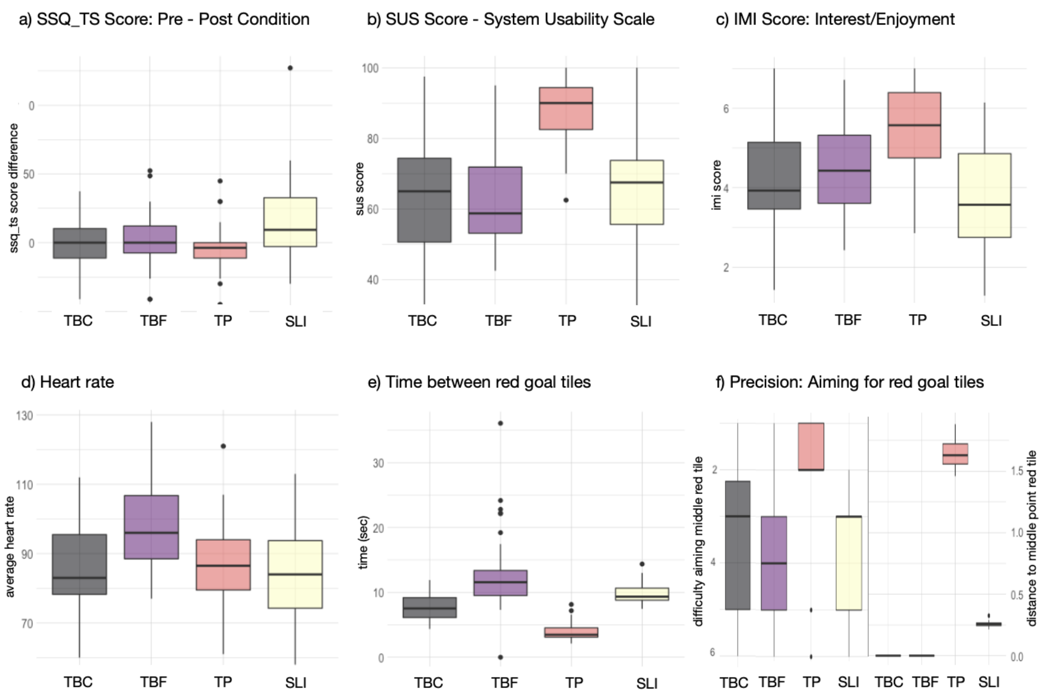

Fig. 4. Six box plots are shown for all four compared locomotion techniques (1) *TB-Controller* as abbreviated to TBC, (2) *TB-Feet* as abbreviated to TBF, (3) *Teleportation* as abbreviated to TP, (4) *Sliding* as abbreviated to SLI. They show (a) SSQ TP Score for the difference between Pre and Post Condition, (b) System Usability Score, (c) IMI Interest/Enjoyment Subscale, (d) Heart rate, (e) Time between red tiles, and (f) left: results of the single item question on precision, right: average distance to the middle point of the red tile when reaching it. Horizontal lines: wiskers representing the reasonable extremes, bottom, and top of the box: 25th and 75th percentiles, thick line inside the box: 50th percentile (median), outliers are shown as circles

the TBL and well-known existing techniques, we wanted to focus in the second study on the TBL techniques themselves.

5.1 Study design

For this study, we decided on a mixed-participants design (TBL techniques: between factor; scenarios: within factor) to give participants enough time to get familiar with one LT and reduce fatigue due to prolonged experimental duration. With this study, we answered the following research question:

RQ2: *How do participants experience* TB-Controller *or* TB-Feet *locomotion in a maze-like and a museum-like virtual reality scenario?*

5.1.1 Conditions. We used two scenarios in this study: (a) a game (i.e., maze) and (b) a learning (i.e., museum) scenario. We chose these application areas because games and learning applications are commonly used in VR.

Scenario A: Maze. A maze was designed as a game scenario, constructed as a forest with several paths that lead the way to a door that had to be opened. The brown tiles are the path (see Figure 5

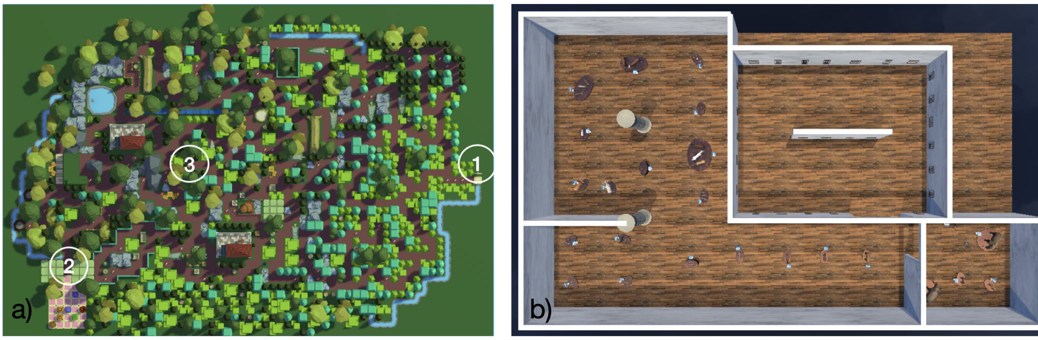

Fig. 5. On the left (a) the maze is shown from a top view. ① is the starting point, ② is the door and finish, and ③ indicates the position where the key for the door can be found. On the right (b) the museum from a top perspective is shown. In the large and smallest room, the animals can be found, and in the middle-sized room, pictures on the wall were placed.

(a)) the user can move on. These paths are surrounded by low poly obstacles to help with orientation but also occlude other paths and create a maze-like character.

The starting point is at position (Figure 5 (a) ①). The goal is located in the top left (Figure 5 (a) ②) and placed behind a closed door (see Appendix Figure 7 (e)) which can be opened with a key(see Appendix Figure 7 (c)). The key is hidden in the middle of the maze (Figure 5 (a) ③). The key has to be found, picked up with the controller, and collided with the door to open it up. On the paths altogether, 52 coins can be gathered, each by stepping on a tile showing a hovering coin (see Appendix Figure 7 (d)).

Scenario B: Museum. The museum is an open space filled with animal statues and wall pictures Figure 5 (b). Each statue is extended with an information board that contains short facts about the animals (see Appendix Figure 7 (a)). The pictures did not have any information. In contrast to the maze, there was no given path for the user. Instead, the player was asked to move freely in the room, explore, view, and learn. The room contained 23 statues with information boards and 32 pictures to explore.

5.1.2 Questionnaires. Similar to the previous study, we used the SSQ [32] to assess cybersickness and the IMI [47] to measure interest/enjoyment. The Player Experience Inventory (PXI) [1] was administered to obtain player experience scores of participants (7-point Likert scale: 1/Strongly disagree – 7/Strongly agree). We used the igroup presence questionnaire (IPQ) for evaluating presence in sense of being there, spacial, involvement, and experienced realism (7-point scale). Additionally, we employed a single-custom item for liking the LT: "How much did you like this locomotion technique?" (7-point scale: 1/Strongly dislike – 7/Strongly like). Similarly, we used a single-custom question for liking the used environment: "How much did you like this environment?"(7-point scale: 1/Strongly dislike – 7/Strongly like)).

5.1.3 Participants. For this explorative study, we had 16 participants (6 female, 10 male, M_{age} = 25.69, SD = 2.59) between the age of 22 and 33. 12 of them were students, three were PhD students at the university, and one was an IT consultant trainee. All of them had a little VR experience, and four of them owned a VR headset.

In total, five reached the given goal in the maze: two of them were in the *TB-Feet* and three of them were in the *TB-Controller* group. For the museum, eight answered the two questions correctly:

two of them were in the *TB-Feet* and six of them were in the *TB-Controller* group. Interviews were only conducted with the first eight participants.

5.1.4 Procedure. After signing an informed consent, the participants were randomly assigned to explore either *TB-Controller* or TBL. Depending on the group, they were tutored in their assigned TBL technique. Afterwards, each group explored the two scenarios ((a) maze and (b) museum, subsubsection 5.1.1) for 15 minutes. The order of scenarios was counterbalanced.

In the maze, the participant's task was to at least collect 30 coins, find the key and reach the goal to open the door with the key. If the user was able to finish the task in less than 15 minutes, they were allowed to end the task early.

The task in the museum was to move around, read all information boards, and observe all images. The participants were informed that they had to answer two questions about the information or pictures after 15 minutes of exploring. After a time of 10 minutes, the participants were allowed to end the session early if they wanted to.

After each scenario, the participants had to answer questionnaires (see above). In the end, after finishing both scenarios, the participants were interviewed with audio recordings. The volunteers were given 10 Euros as remuneration.

5.2 Qualitative Findings

We recorded and saved 1:04:27 hours of spoken interview time pseudonymously from eight of the participants. We used Dovetail[6] to transcribe and analyze the recordings (quotes presented in this paper are translated into English). For evaluation, we used a hybrid thematic analysis approach, using elements from reflexive analysis and codebook-oriented thematic analysis [9–11]. Two authors were involved in the analysis process. Prior to coding, they constructed six deductive categories related to their research question in a discussion: *Enjoyment*, *Usability*, *Maze*, *Museum*, *Physical Activity*, *Improvements*.

During the first round of interview analysis, we developed inductive codes within these categories. Therefore, each interview was first coded separately by both of the analysts. Then, they went through a session where both researchers compared the codes and adjusted them if necessary, to a new set of codes. After all, interviews went through this process once, the final codebook was checked again with all interviews. By doing so, we aimed to avoid that later added codes were missing in one of the earlier interviews.

The final codebook was then spread out on a board. With the involvement of both analysts, we tried to match them into thematic categories and formulated the first draft of themes. These themes were then applied in a discussion session of both analysts to a second round of going through each interview. During that process, the themes were extended, reformulated or merged if necessary, resulting in five final themes.

Theme 1:* TB-Controller *perceived as easy to use, relaxing, and safe technique, however, it was also slow and unrealistic for some. All four participants perceived *TB-Controller* as easy to use and learn. One participant explained it as "Yes, well, it was a very direct method you always moved at the same distance. You didn't have to aim it exactly [...]." (P4). Another explicitly said "So once, you probably learn it very quickly because you only ever have to use one button." (P7). One participant particularly pointed out error-less use of this locomotion technique: 'You can't really do anything wrong. You can just press right left, you go in that direction or you turn yourself around and then you can go the direction the same way." (P6). However, in some instances, a participant experienced problems due to having a hard cut of change of the moving angle: "But it's hard to see

[6]www.dovetailapp.com

exactly which direction the controller is pointing because it's pointing at about a 45-degree angle. Then you just went somewhere instead of where I wanted to go." (P4).

The participants did not experience cybersickness, and some even compared the *TB-Controller*'s low level of cybersickness with possible scenarios: "Yes, for example, if you were to move yourself instead of using controllers, it's probably also possible that you'd get nauseous or dizzy again quickly"(P6). One participant speculated if the big jumps of teleportation could cause higher cybersickness than "always move[ing] very briefly" (P7).

This method was also perceived as very relaxing: "You don't have to aim exactly [...]. You don't have to hold the controller with an outstretched arm [...]. You can let your arm dangle like this but press the button. So you don't have to strain so much when you have to lift your arm somewhere." (P4). Further, it was considered as a safe technique: "In theory, you don't have to move from the spot. So if you do, you just have to turn. But you don't run into a TV." (P2).

While the *TB-Controller* was generally praised, some participants also criticized this technique to cause slow locomotion: "That you can only go one step at a time. That makes it a little slower." (P7). The unrealistic feature of the *TB-Controller* was not appreciated: "when you move yourself, it is still something else as if you do it via controller" (P6).

Theme 2: The participants presented different opinions on the* TB-Feet*; some found it intuitive, easy to use, and safe, while some considered it slow and pointed out balance, exertion, and accessibility concerns. Some participants found the *TB-Feet* locomotion being "funny" (P3), "intuitive" (P3), and "easy to use" (P1). For one, stepping movement created an incentive to continue to this motion and therefore, a struggle at the beginning: "because you think, [so if] you want to run automatically in that direction, but you have to stop in one place" (P8).

Similar to *TB-Controller*, *TB-Feet* is also considered safe and not causing cybersickness: "So the space is kind of infinite, you're not afraid you're going to run into it somewhere, and you don't get sick." (P3).

Some concerns were raised: First, the necessity of "good balance" (P3). Second, a participant pointed out that "it's [*TB-Feet*] not feasible for everyone. Well, when someone is in a wheelchair, they can't exactly move well."(P8).

One participant asked for more smoothness "because sometimes it got stuck and then I just not progressed [...]. But if that runs, then it actually fits" (P1). On one side, one participant explained "I sometimes had the problem that I was somehow too far in one direction" (P5) but on the other hand some participants mentioned the locomotion technique being slow "That takes a long time if you want to get from one corner to the other." (P3).

Theme 3: While both scenarios received positive comments, the maze was often preferred compared to the museum scenario. The many playful details and hurried task of the maze scenario was the distinctive reason for this. Overall, some participants appreciated the open space environment design of museum: "The pictures were interesting and the space was really cool. Wasn't a cramped feeling, but rather open. Also because the roof was open." (P8). For one, realistic aspects of the museum environment also had a positive effect: "It was very real the environment, so you could imagine the animals and everything well in reality I think. And the pictures looked like that. So I thought it was quite well done." (P6). However, some did not like this open space design because it was "a bit of a bare space" (P2). Thus, "it was a bit of a stretch to cover the rather long distances between exhibits." (P5). Even one compared this scenario to the maze, and considered it a "bit more boring than the maze because I [they] had to cover longer distances simply all the time and then read something again." (P7).

Compared to the museum, the participants commented more positively about the maze scenario. They considered the maze "[...] more fun. Oh, and also, I thought it looked nice and in general, it was just a nicely designed environment where you enjoyed being, I thought." (P5). Some emphasized the role of playful tasks in the maze, and its positive influence on their experience: "I also thought the idea with the coins was cool because you would collect something. The task with the key I also found cool, if you then have an additional task, which also causes a bit of stress and you just want to finish the thing good. Well, I thought the idea with the labyrinth was cool because, I don't know, I think most people like mazes. I like mazes." (P8). Nevertheless, some felt "disoriented" (P3).

Theme 4: Game or Maze-like VR applications seem to be more fitting for TBL instead of teleportation due to it being more distracting/exciting and task-driven. Large open and calm scenarios (like the museum) with long moving distances seem to be more fitting for faster locomotion e.g. teleportation. Regardless of the condition, participants considered the maze as an appropriate scenario for TBL; a *TB-Controller* participant: "So, for the layout [...], of the environments that we had, it actually fit completely well because everything, especially the labyrinth for example, was also built a bit like a chessboard and then it just fit quite well."(P7), and a *TB-Feet* participant: "Um, that suited the path because with the locomotion option you can only go in four directions. But that's exactly what makes sense in the game, that you only have to choose one of the four directions, because it's an angular path, so it goes in quite well."(P1).

Further reasons for liking and accepting *TB-Feet* in the maze scenario were the game aspects that caused a distraction. Participants felt like they "progressed faster"(P1), were more motivated ("when you found coins, it was cool, so it was motivating"(P1)), and distracted ("because one had just the distraction of the locomotion method. So you also had to somehow strain your brain to somehow memorize the paths. So I didn't pay so much attention to how much it was annoying for me to be able to move only with my feet."(P5)). One participant explained: "[It] was somehow more exciting because you were really under time pressure and tried to get through the labyrinth as quickly as possible."(P5).

Interestingly, the maze participants wished for no teleportation instead of *TB-Feet* or *TB-Controller*. Due to teleportation being more "unnatural"(P6) or being a perfect fit for the scenario ("I think it [(*TB-Controller*)] was actually a perfect fit for that. Because if I had teleportation or something like that, I couldn't teleport that far. If you always have to turn around and stuff like that. That's why it actually fits well with what I had there."(P7)). Similarly, some kind of sliding locomotion in the maze was rejected by P4: "Because the path and the curves are virtually always one step long. You always have to take exactly one step anyway. So moving so slowly that you glide or something will not be worth it.".

For the museum the opinions were different. The *TB-Feet* was often disliked due to not being an efficient choice: "It wasn't that much fun because it took forever to get somewhere. And then, because you only have the four directions, it was a bit complicated to walk around a figure like that."(P1). One *TB-Feet* participant said "I thought it was bad in the museum because you were really only focused on how exhausting it was."(P5).

Interestingly, in contrast to the maze participants, teleportation was often wished for by participants after performing the museum. A participant using *TB-Feet* said "So, for example, I would like it if you could just, I don't know, choose somewhere where you want to go next. And then you teleport there, for example, and that's it."(P5). A participant, who experienced *TB-Controller*, wished for *Teleportation* because it would be "easier"(P7) and "faster"(P7) due to the open space since "there are no sections or curves or something like in the labyrinth"(P4). There were individual instances that suggested some variance: "So at the beginning teleportation, but at the end more in the direction of moving with the feet. Because it's more real, I think. Teleporting at first is actually too easy, [...]. So there are no challenges behind it, I think personally."(P8).

Overall, maze or game-like (collection coins,...) environments were mentioned as strongly fitting for both TBL, while open and calm environments like the museum probably need locomotion techniques like *Teleportation*.

Theme 5: The* TB-Feet*'s physical activity was perceived sometimes more (museum) sometimes less (maze) exhausting what some participants liked while others disliked it. In comparison* TB-Controller *was perceived as not very exhausting. For *TB-Feet*, opinions were different. P3 thought it was not exhausting while P8 at least mentioned "No, not really. If you had both legs then not, if only one leg, then at some point, yes."(P1). One participant differed depending on the scenario: "In the first task [(Maze)], not in the second task because it was on time and you had to collect certain things on time, yes. Then I was already sweating. In the first one, I had a big area where I had to stand and read and observe more than I had to physically move or reach a certain goal at a distance and still collect things in time. That means I had the stress factor and the collection factor on top of that."(P8)

Participants mentioning exhaustion in *TB-Feet* had either the opinion that it was "Good, but exhausting."(P8) and "so that's what it's really about"(P8) and "It feels a bit like being active yourself. Yes, and you know exactly in which direction you're going."(P1) or on the other side disliking the exhaustion "[...] actually in itself I do not like it. Disadvantages yes, just that it is [just] tiring to use."(P5) This participant further explains more clearly their dislike: "For one thing, it was energy-consuming to move his foot into different positions all the time. So forward or to the side. If you then wanted to run a longer distance, for example straight ahead, you had to keep your foot in the air for a long time, which was uncomfortable. And you also had to move your foot up and down once for each step, which was also energy-consuming and led to a bit of really feeling your foot."(P5)

The *TB-Controller* locomotion was not perceived as exhausting from P2, P4, and P6. Only P7 said "Nah, so if you have to move a long distance maybe yes because you have to press often [but] otherwise not."(P7)

5.2.1 Further Ideas: We also asked for ideas of alternative scenarios for TBL techniques and got some improvement ideas.

Improvement for TBL. Both *TB-Controller* and *TB-Feet* wished for faster movement options, especially when having long distances: "maybe have a function that you could move larger distances directly somehow faster. Don't know, if you stay maybe with his foot there in front, that it then directly covers several fields."(P5) For the museum, some participants also wished for diagonal movement options independent of the used TBL because "sometimes it would have been more diagonal instead of straight ahead or to the right"(P4). A *TB-Controller* participant suggested "I would probably like it if I could always switch between the two(*TB-Controller* and *Teleportation*), depending on the environment, but I wouldn't swap completely [to teleportation]."(P7) A *TB-Controller* participant wished to "use another controller that doesn't have such a smooth circle and then you just have front and right and left as separate buttons"(P4).

Alternative Scenarios for TBL. *TB-Controller* and *TB-Feet* was mentioned to be fitting for games (P5, P6) but "action-packed games or something like that might be a bit worse."(P4)

A *TB-Feet* participant listed "Like on the treadmill. Treadmill training then also does jogger training, then for example laps running in the stadium, also quite cool simulator or anything to do in training exercise. Or apartment tour for example also quite cool, city tour, tours also cool. Oh yeah, sightseeing."(P8) and a *TB-Controller* participant also mentioned "If you have architects build something like that, that would be quite good to walk through or something, and that's where I think you can use that quite well." (P4)

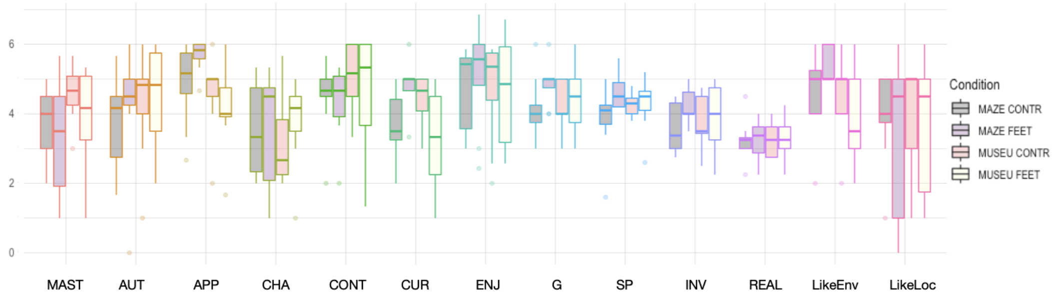

Fig. 6. The figure shows box plots grouped in Conditions ((a1) maze with *TB-Controller* (a2) maze and *TB-Feet* and (b1) museum with *TB-Controller* and (b2) museum with *TB-Feet*) and subscales or custom questions (PXI: Mastery; PXI: Autonomy; PXI: Audiovisual appeal; PXI: Challenge; PXI: Ease of Control; PXI: Curiosity; IMI: Interest/Enjoyment; IPQ: sense of being there; IPQ: spacial presence; IPQ: Involvement; IPQ: Experienced Realism; Custom: Like Environment; Custom: Like locomotion technique)

One interesting suggestion was board games from a *TB-Controller* participant: "I think in VR games like that, if you're kind of in VR if I'm a piece on a board game or something and I can only move like that anyway, for example in chess or something where I can only move one square anyway and yeah in games like that probably the closest" (P7).

5.2.2 Quantitative Results. We report box plots of the quantitative results in Figure 6. However, we acknowledge that sixteen participants (eight for each locomotion group) represent a rather small sample size for a between-participant designs, which is why we abstained from performing statistical tests. A table with mean values and standard deviation can be found in the Appendix Table 2. We can find tendencies towards better player experience (audiovisual appeal, challenge, enjoyment, like environment) in the maze game, but also a bit more mastery, autonomy, ease of control in the museum. Mastery, audiovisual appeal, challenge, sense of being there, spacial presence, and involvement was slightly higher for the *TB-Feet*. Overall, enjoyment scores are very high.

6 DISCUSSION

Overall, our results show that TBL can be an accepted and enjoyable locomotion technique if the scenario supports the benefits through a narrow and detailed environment. Furthermore, all participants accepted *TB-Controller*, while *TB-Feet* depends on how much a participant likes physical activity.

Cybersickness and Enjoyment. Both studies show low or no cybersickness scores for both TBL techniques. These results demonstrate that both TBL techniques do not significantly reduce participants' cybersickness-related well-being. Acceptance goes hand in hand with enjoyment, which we confirm by high enjoyment values in both studies for the TBL techniques stronger, however, in the second study.

Usability. The SUS scores in the first study for our two TBL indicate acceptable usability between "ok" and "good" usability level [3]. These results are consistent with the results of the second study, where both techniques are mentioned to be easy, intuitive, and safer than walking but in general slow. For *TB-Controller*, some participants mentioned having to get used to the direction change through the viewing direction, but here some future work could evaluate different versions and angles of direction change to further improve the locomotion technique. The same can be said for the *TB-Feet* where different ways of implementing the tapping on the ground could be tested.

Probably an implementation that uses gesture tracking through the Head-mounted Display like in Xu et al. [60] could be considered instead of using trackers. Nevertheless, these results support our expectation that using TBL can be not only fun but also easy to learn and relatively safe to use.

Speed and Number of Goals. In terms of speed and number of reached goals, *Teleportation* is the significantly fastest, followed by *TB-Controller*, and *TB-Feet* is the slowest. The possible jumping size of *Teleportation* makes a very big difference here. For environments where users only want to fast overcome bigger distances, speed is a large advantage. However, speed can have disadvantages, like over-jumping details that are important or interesting to see. In some games or applications, the designer might want to force the user to take time and focus on details or just be challenged. Interpreting this, speed can be an advantage or disadvantage depending on the task in a scenario, as we can see in our results of the second study. We assume in the right scenario TBL could gain higher enjoyment and presence than *Teleportation* through having similar characteristics like *Sliding* concerning natural movement speed. Natural moving has been shown to yield a higher presence than *Teleportation* [49]. However, we did not find any significant differences between conditions in the presence scores of participants. We suggest further investigation of our conditions with different environments and tasks.

Precision. Our measures show higher precision in aiming for an exact point of TBL due to the way it is implemented compared to the standard implementation of *Teleportation* and *Sliding*. Because TBL uses the tiles and automatically aims for the middle point, missing, e.g., coins when running over them is less likely. Depending on the scenario (picking up coins vs. strolling around in an environment), the "tile-snap" can be seen as an advantage for precision or a disadvantage for freedom of control. Here, we want to note that "tile-snapping" can be implemented for other techniques as well, but they might lose some of their acceptance and likeliness. However, we also suspect that this would be environment-dependent. For example, when Frommel et al. [22] tested fix-point teleportation and free teleportation in open zoo grounds, the free teleportation was overall liked more. This could coincide with our assumption that free and open environments are more fitting for locomotion technique like free *Teleportation*, while narrow environments and tasks that need precision are more fitting for "tile-snapping" like our TBL. Here, some more investigation is needed, where different "tile-snapping" techniques are contrasted. Based on our qualitative analysis, we expect that the speed a person travels through a specific environment has an effect that will be the same for 'tile-snapping" *Teleportation* and the free *Teleportation* but could differ regarding precision.

TB-Feet *and physical activity.* At last, the *TB-Feet* was designed to create a TBL that subconsciously heightens physical activity. While our results, similar to those of Masek et al. [40], show a higher heart rate with *TB-Feet* than all other compared locomotion technique, we do not reach a level of high exercise intensity [38]. Still, balancing on one foot and slight physical activity can contribute to creating health improvements [53], similar to other approaches [23]. Important to notice, however, is that liking *TB-Feet* in our study as connected to participants liking physical activity in general. The benefit of having both TBL techniques is their interchangeability. Users could easily switch between the two techniques, while unathletic persons are less disadvantaged when getting tired.

Environments and TBL. Regarding the two scenarios of the qualitative exploration study, participants noticed the maze had many details, a narrow environment without long distances, many direction changes fitting to the four directions, and an engaging and distracting task. On the other hand, the museum was more cold and empty, with long distances and open space in between. The task was more explorative, relaxing, and learning-based. The tight spaces of the maze make far jumps unnecessary or impossible and create an environment where the path is part of the challenge. As already indicated above, these differences in the environment contribute to liking TBL or mentioning to wish for a locomotion technique that would be similar to *Teleportation*.

For improvements, participants wished for a diagonal addition which could be evaluated in future work and could benefit liking of open calm spaces with TBL due to less challenge and more direct (e.g., faster) movement.

Summary and Takeaway. Overall, our results strengthen our assumption that both TBL will be valuable extensions of locomotion techniques for VR by creating new challenges, experiences, and for *TB-Feet*, physical activity. Being enjoyable and easy to use without discomforting the user through cybersickness, they can be especially useful for game-like environments that take advantage of the slow speed, precision, and narrow environments. Furthermore, they keep the player busy with tasks and distract them from the exertion of *TB-Feet*. Both locomotion technique are easily interchangeable and can thus be used depending on the situation and motivation for physical activity. Our qualitative feedback shows that TBL has a lot of potential for future VR games, enabling tile-based board games or rhythmic VR games where the step-like movement can be aligned with music.

6.1 Limitations

We acknowledge that small sample sizes, especially in the second study for the quantitative part, could have influenced the results. Therefore, our results are not representative of other groups than university students with an average age of around 25 years. Knowledge of VR systems and familiarity with locomotion techniques like teleportation could have influenced the participants' subjective evaluation as well. Nevertheless, the familiarity factor of the known techniques could have balanced out the novelty effect of the new locomotion techniques.

For our comparison study, we would have liked to have more comparisons with other locomotion techniques to get a better classification of our techniques. However, due to study length, this was not possible but could be interesting for future work. Other promising avenues for future work are to compare the TBL techniques with *Teleportation* in the exploratory scenarios (i.e., maze and museum) to understand how values like enjoyment, usability, and presence change depending on the scenario. These comparisons are, however, beyond the scope of this work, where we aimed to show the feasibility and acceptance of the TBL techniques.

We acknowledge that many other implementations of TBL techniques are possible, for example, to use eye gaze direction for aiming, which could be explored in future work. We decided to use the head direction to indicate the direction because head direction-based locomotion is a commonly used technique [56, 59]. We did not want to increase the workload of participants by introducing complex combinations to decide on a relevant direction, and our solution could be easily implemented without additional hardware use tracking other body parts, and therefore it has more possibility of being applied to other applications as well.

While we do not expect serious safety issues in the use of our setup and environment, we also acknowledge potential safety issues that may arise from physical activity and use of the VR HMD setup (e.g., people can collide with objects while wearing VR and moving fast).

At last, we want to draw attention to the fact that all parts involved in doing the analysis, especially the qualitative one, are human-computer-interaction-centered researchers with a high interest in VR, which could have influenced the thematic analysis and interpretation of results.

7 CONCLUSION & FUTURE WORK

In this work, we explored the concept of tile-based locomotion for VR by presenting two new techniques: *TB-Controller* and *TB-Feet*. We evaluated them quantitatively and qualitatively in two user studies. In general, participants enjoyed both TBL techniques with a few exceptions concerning the open space museum scenario. Both studies show that in our scenarios, TBL techniques do not generate a noticeable level of cybersickness. Both TBL are accepted with easy and intuitive usability, however, the *TB-Feet*'s rating highly depended on users' preference for performing physical movement. Both techniques are easier in aiming for an exact position compared to tile-independent movement implementations like the *Teleportation* and *Sliding* techniques we compared it to. Compared to *Teleportation*, both TBL techniques and *Sliding* are slower which can be beneficial or frustrating depending on the task and environment. Through our two environments (maze and museum), we gained new insights into environmental preferences for locomotion techniques. Our results indicate that TBL is especially suitable for narrow and crooked environments (e.g., a maze), where fast locomotion like *Teleportation* would be too fast and hard in aiming for small details. While both locomotion techniques can be further improved and investigated, we consider TBL opening new areas for VR to implement and investigate, like real-size boardgames and other tile-based games building upon the wide range of tile-based VR games.

ACKNOWLEDGMENTS

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A APPENDIX

A.1 Quantitative results of second explorative study

Table 2. The mean and standard deviation for IMI (Interest/Enjoyment), PXI(Mastery, Automomy, Audio visual appeal, Challenge, Ease of Control, Curiosity, SSQ (Cybersickness), IPQ (sense of being there, spacial presence, involvement, experienced realism), Liking of Locomotion, Liking of Environment

Cond	IMI(Enj)		PXI MAS		PXI AUT		PXI APP		PXI CHA		PXI CON		PXI CUR	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
(A) Maze	4.95	1.35	3.52	1.40	3.95	1.57	5.27	0.99	3.56	1.50	4.39	1.07	4.25	1.02
(B) Muse	4.67	1.50	4.20	1.29	4.33	1.55	4.39	1.25	3.47	1.30	4.81	1.40	3.83	1.26
(1) TBC	4.74	1.32	4.14	1.08	4.00	1.46	4.72	1.17	3.35	1.30	4.75	1.05	4.02	0.93
(2) TBF	4.89	1.55	3.58	1.59	4.29	1.67	4.93	1.24	3.68	1.49	4.45	1.43	4.06	1.37

Cond	SSQ TS		IPQ G		IPQ SP		IPQ INV		IPQ REAL		LIKE LOC		LIKE ENV	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
(A) Maze	22.90	20.34	4.50	0.89	4.23	0.88	3.92	0.69	3.25	0.61	3.62	1.85	5.00	1.03
(B) Muse	19.40	19.70	4.31	0.87	4.27	0.58	3.82	0.84	3.29	0.56	3.81	1.72	4.18	1.27
(1) TBC	20.10	21.97	4.18	0.83	4.05	0.76	3.67	0.72	3.26	0.56	3.93	1.38	4.56	1.20
(2) TBF	22.20	17.98	4.62	0.88	4.46	0.67	4.07	0.76	3.28	0.61	3.50	2.09	4.62	1.25

A.2 Additional pictures of scenarios

Fig. 7. (a)-(b) Museum scenario: (a) An animal with information board. (b) Paintings on the wall to look at. (c)-(f) Maze Scenario: (c) The key to open the door, (d) The coins that can be collected, (e) The door while it is closed, and (f) when the door is open.

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