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# Running in triangles: the effects of continuous and discrete locomotion techniques on spatial orientation in virtual reality - a comparative study

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As we navigate in real-world environments, our egocentric location representations are seamlessly and automatically refreshed. However, when traversing a virtual space using magical locomotion techniques, it is common to experience disorientation and discomfort due to insufficient sensory input, particularly related to bodily movement. To avert disorientation and discomfort (cybersickness) in virtual reality without limiting overall usage by employing more natural locomotion techniques (redirected walking, treadmill, etc.), alternative approaches must be explored. In the presented experiment, participants engaged in a spatial updating task within a sparse virtual scene and were instructed to return to an initial position following simulated movements. They performed this task using the teleportation method, a purely continuous locomotion approach without self-motion (dash), and a combination of both techniques. All three methods were evaluated over short (3 m) and long (13 m) distances, and cybersickness along with cognitive load were assessed for every condition. Overall, the findings indicated no notable differences in cybersickness, cognitive load, and spatial localization across the conditions, although cognitive load was reduced and spatial localization was improved at shorter distances. For the selected scenario, the results suggest that the extent of continuous locomotion offers only a minimal advantage in spatial orientation and virtually no downside concerning cybersickness.

KEYWORDS

**cognitive load, cybersickness, locomotion, spatial orientation, TCT, virtual reality**

## 1 Introduction

In recent years, extensive research has focused on locomotion in virtual reality (VR), driven by the critical role it plays in shaping user experience. Continuous movement or teleportation are traditional approaches that present unique challenges that can either enhance or diminish the user's sense of presence and spatial orientation. Spatial orientation could be defined as the sense of position and orientation, which is based on a cognitive map that represents our spatial knowledge about the environment (Bowman et al., 1999). When individuals navigate through their physical surroundings, they can update their cognitive representation of their body position in relation to the surrounding context, thus facilitating effective spatial orientation (Riecke et al., 2002). Spatial updating synthesizes a variety of

signals regarding one's movement from diverse sensory modalities. This includes information from the vestibular system, proprioceptive feedback, visual and auditory cues, as well as cognitive spatial representation. In virtual settings, these sources of information are often either insufficient or entirely inaccessible to the user. Particularly, the absence of body-based cues caused by spatial limitations can impair spatial awareness. Poor spatial orientation in VR can lead to confusion, disorientation, and a decrease in overall task performance (Chen et al., 2007).

There are numerous studies comparing different forms of locomotion in VR with respect to various factors such as spatial orientation, cybersickness, presence, or ease of use (e.g., (Cherni et al., 2020)). Among these, teleportation often performs particularly well, as it minimizes negative effects such as cybersickness and can be implemented even in limited physical spaces (Prithul et al., 2021). The advantage of teleportation is that the immediate perspective change reduces cybersickness, as it prevents vection-related discomfort. However, this lack of continuous movement and optical flow can, in turn, negatively affect spatial orientation, making it harder for users to maintain a sense of direction and position within the virtual environment (VE). Several studies have compared teleportation with other VR locomotion techniques. Teleportation generally reduces cybersickness and is more efficient compared to joystick use or continuous methods (Langbehn et al., 2018; Coomer et al., 2018; Bozgeyikli et al., 2019), but it often impairs spatial orientation and path integration, leading to greater errors in tasks such as triangle completion (Coomer et al., 2018; Paris et al., 2019; Cherep et al., 2020). Despite the advantages of teleportation in reducing cybersickness, its impact on spatial orientation remains a challenge due to the absence of body-based cues. To address this, newer locomotion techniques have been developed to combine the benefits of continuous movement with teleportation. Griffin and Folmer (2019) introduced "out-of-body locomotion", a vectionless approach that reduces the need for teleportation and mitigates cybersickness while maintaining control. Similarly, Bhandari et al. (2018) introduced the "Dash" method, which combines limited optical flow during viewpoint transitions with teleportation to reduce spatial disorientation. They aimed to enable a small amount of optical flow during teleportation to improve the spatial orientation without causing any cybersickness symptoms. This dash method was characterized by using a rapid continuous viewpoint translation with a constant velocity of 10 m/s. In their within-subjects study with 16 participants, they investigated traditional teleport against the dash method in a variation of the triangle completion task (TCT) with regard to spatial awareness, cybersickness, efficiency and preference. They observed a significant difference in path integration error, with dash showing less error. There was no significant variation in cybersickness, but dash had a lower average value. Interviews revealed that 15 participants favored dash for spatial awareness, while one saw no difference. Eleven participants found regular teleport most efficient, two preferred dash, and three noted no difference. In terms of preference, twelve participants preferred dash, while four preferred regular teleportation. In summary, a small improvement in path integration and cybersickness can be recognized with the dash method. Even if these differences are not significant, the combination of teleport with a proportion of continuous movement seems to be a research approach worth investigating.

Based on these findings, we decided to investigate the effects of different locomotion techniques. To be more precise, this work assessed whether techniques with different amount of continuous translation information affect the spatial updating, the perceived cybersickness symptoms and cognitive load.

# 2 Methods

## 2.1 Participants

We conducted an a-priori-power analysis with G*Power (version 3.1.9.7) with the following parameters for ANOVA (repeated measures, within factors): effect size f = 0.35; alpha-error probability: 0.05; power: 0.95; number of groups = 1, number of measurements: 3, resulting in a total sample size of N = 23. Overall, 20 participants took part in the experiment. We had to exclude the data of two participants from the analysis due to technical problems, resulting in a final sample size of N = 18. They had an average age of 35.78 years (SD = 6.30 years), and seven participants were female (39%). Except for one, all participants were right-handed. All participants had normal or corrected-to-normal vision, participated in the study voluntarily, and were informed that they were free to abort the experiment at any time. The full experimental session took approximately 60 min (including 30 min measuring time), and all participants received monetary compensation.

## 2.2 Materials

The experiment was conducted using a Meta Quest 2 head-mounted display (HMD) with a refresh rate of 72 Hz, paired with Touch Controllers. The HMD was connected to the operating computer via Link Cable. In the VE, developed using Unity 3D (version 2021.3.3f1), participants saw a plain covered in snow, which was uniform, i.e., without elevations or visual features, and a blue atmospheric cloudy sky (see Figure 1A). To provide distant landmarks, four trees (based on the visual cues described by Breitkreutz et al. (2022) were placed at cardinal directions (west, north, south, and east) approximately 20 m from the center. Each tree was approximately 3 m tall with a trunk diameter of 1 m. While the trees were similar in appearance, differences in cast shadows, caused by the lighting, provided additional visual variation.

## 2.3 Design and procedure

All procedures were determined by the applicably body (Ethics committee of the Chemnitz University of Technology) not to require in-depth ethics evaluation (101606517). Three different forms of locomotion, which differ in terms of the amount of continuous movement information, were investigated in the study: (i) Teleportation: Participants selected a target location by pointing with a curved laser beam. Once the destination was confirmed, the viewpoint instantly transitioned to the selected

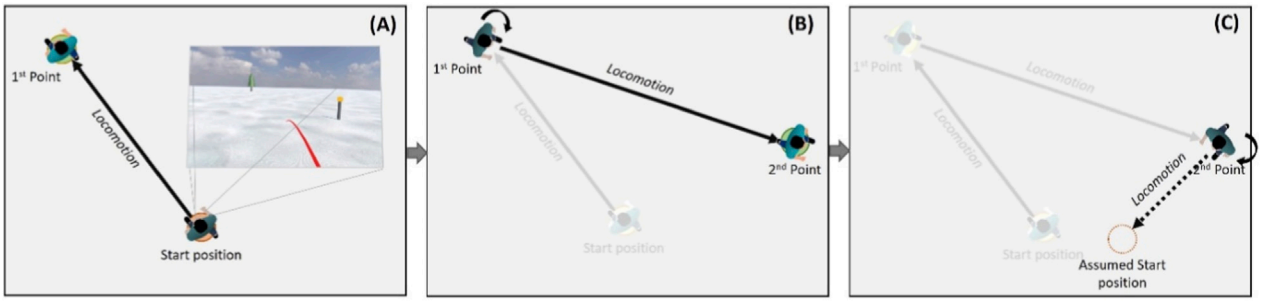


FIGURE 1
Schematic illustration of a single trial: **(A)** participants point to the first target and move directly toward it, **(B)** participants point to the second target and move directly toward it, and **(C)** participants return to the starting position, which is not visually displayed

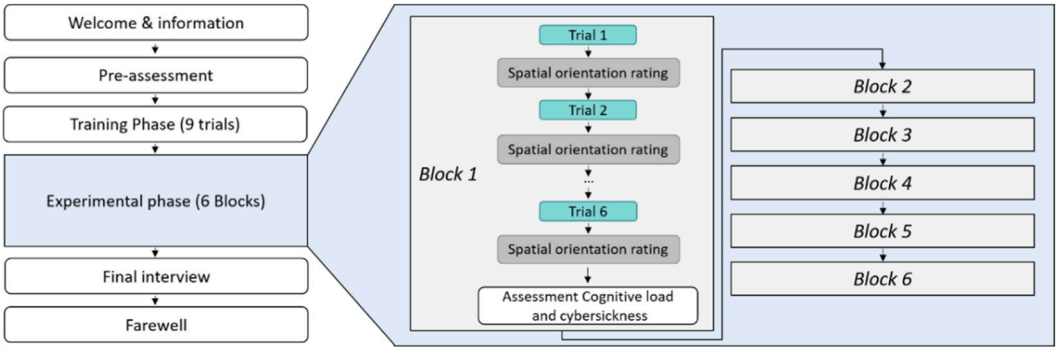


FIGURE 2
Procedure of the main study.

point. (ii) Dash: Participants selected the target by pointing, after which they were moved continuously at a speed of 3 m/s to the destination. (We set the dash speed to 3 m/s, based on a pre-study with VR experts, to ensure a noticeable yet realistic movement across both short and long triangle distances). This translational movement was automatic and could not be controlled mid-motion. (iii) Dash + Teleportation (later referred to as *combination*): Participants pointed to select the target location. They were then teleported halfway and subsequently moved continuously for a fixed duration of 1 s to cover the remaining distance, resulting in distance-dependent movement speeds. Prior to the main study, a preliminary test (N = 8) was conducted in VR to examine whether participants could distinguish between the different locomotion types or not, and to find out which parameters for dash of the combined locomotion type were most pleasant while simultaneously least cybersickness-inducing. A total of six different triangles with varying interior angles were used as paths in a TCT. These triangles varied in their homing distance - either 3 m (small triangles) or 13 m (big triangles) - and in the starting position, which was either 2.5 m or 5 m from the triangle's center. By using both small and big triangles, we aimed to assess whether the size of the triangle influenced locomotion performance and user preference. Two different start positions were used to achieve an increased variability in the triangular paths. Each triangle was presented as both the original version with right-hand turns and a mirrored version with left-hand turns, so that a total of 12 triangles were used. The conducted study included six distinct experimental conditions, which can be derived from the two independent variables: (i) the locomotion variable, with its three types: teleport, dash, and combination (teleport + dash); and (ii) the triangle size, divided into small and big. Following this notion, the experiment had a 3 × 2 within-subject design.

The procedure (see Figure 2) included a general questionnaire, a baseline assessment of cybersickness conducted before participants donned the HMD, and a training phase of nine trials. During the first five training trials, the participant received feedback in the form of a green hemisphere that appeared at the actual starting position. The main experiment consisted of 36 trials, divided into 6 blocks of 6 trials each. Each block corresponded to a single locomotion method and a fixed triangle size, while individual triangles within a block varied in type (three different triangles) and orientation (normal or mirrored). Triangles within blocks were randomized, and the order of the six experimental blocks was counterbalanced across participants using a Balanced Latin Square design to control for potential order effects. The average trial durations were 26.4 s for teleport, 28.2 s for combination, and 32.1 s for dash.

In all three conditions, the participants pointed to the first target point to move there (see Figure 1A). To ensure an even movement on the first two triangular legs and to prevent additional movements, only movements directly to the first target point were possible. In all

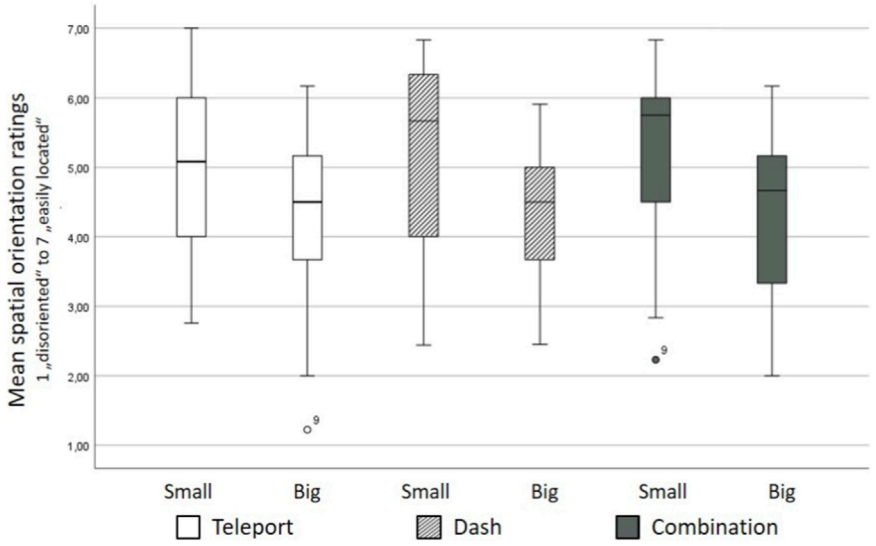


FIGURE 3
Mean spatial orientation ratings for all locomotion methods and both triangle sizes ranging from 1 ("disoriented") to 7 ("easily located").

three conditions, the participant's line of sight was kept constant to the initial line of sight upon reaching the target point. This means that a real body rotation was necessary to see and move to the next target point. After reaching the first target point, the marking of this disappeared and the second target point was marked. Just as with the first target point, the participants moved to the second target point (see Figure 1B), which also disappeared when reached. After that, the participant's task was to move back to the nonvisible starting position on the shortest route (see Figure 1C). For this homing route, the participants carried out real rotations and simulated translations. In contrast to the translations of the first two sides of the triangle, for the homing route, the participants had an unlimited number of translation processes at their disposal. After they moved to the assumed starting position, they logged in their current position by pressing a button and went ahead to the next trial.

The entire experiment was performed while the participants were seated on a swivel chair. After each trial, the participants verbally rated their spatial orientation ("In accomplishing the task . . . "; 7-point-scale as semantic differential ("I was disoriented" – "I was able to easily locate myself")) and manually started the next trial. After each block, they removed the HMD and rated the answers to the cybersickness (measured with the MIsery SCale (MISC) (Reuten et al., 2020)) "How do you assess your current condition/feeling?"; 11-point scale (from 0 = "no discomfort" to 10 = "just before vomiting")) and cognitive load (measured with the Mental Effort Rating Scale (Paas, 1992)) "My mental effort was . . . "; 9-point scale (from 1 = "very, very low" to 9 = "very, very high") questions.

# 3 Results

While significance tests are reported in the following, the results and especially nonsignificant results should be interpreted with caution due to the limited sample size and warrant replication in future studies with a larger sample to ensure the robustness of the findings. All data from the Unity project and survey tool were pooled in Microsoft Excel 2016 and analyzed using IBM SPSS Statistics (v29.0). Since SPSS does not provide confidence intervals for partial eta squared, the 95% confidence intervals were calculated using the online effect size calculator by Uanhoro (2017). The aligned rank transform (ART) analysis was implemented using the ARTool package in R. The significance level was set at 0.05, and effect sizes were interpreted following Cohen (1988). Outliers were identified using boxplots and a ±2 SD criterion for z-scores. Detected outliers were winsorized according to Field (2013), i.e., z-scores below −2 were set to −2, and those above 2 to 2. Normality was tested using the Kolmogorov–Smirnov test. No correction for multiple comparisons was applied, as only single pairwise comparisons were conducted. To further analyze the data, we calculated the means and standard deviations for the subjective spatial orientation ratings, the cognitive load and cybersickness for every participant of each condition.

## 3.1 Spatial orientation ratings

As can be seen in the boxplot in Figure 3, in terms of subjectively perceived spatial orientation, the dash condition achieves the best (small triangles: $M = 5.24$ ($SD = 1.25$); big triangles: $M = 4.35$ ($SD = 0.83$)) and the teleport condition the worst ratings ((small triangles: $M = 5.00$ ($SD = 1.18$); big triangles: $M = 4.21$ ($SD = 1.34$)), for both triangle sizes. Mauchly's test indicated that the assumption of sphericity had not been violated for locomotion type, $\chi 2$ (2) = 3.91, p = 0.142. A repeated-measures ANOVA showed that the spatial orientation rating was not significantly affected by the type of locomotion, F (2, 34) = 0.96, p > 0.05. However, there was a significant large main effect of the triangle size on the spatial orientation ratings, F (1, 17) = 29.15, $\eta P^2$ = 0.63. The pairwise comparisons revealed that the spatial orientation rating was

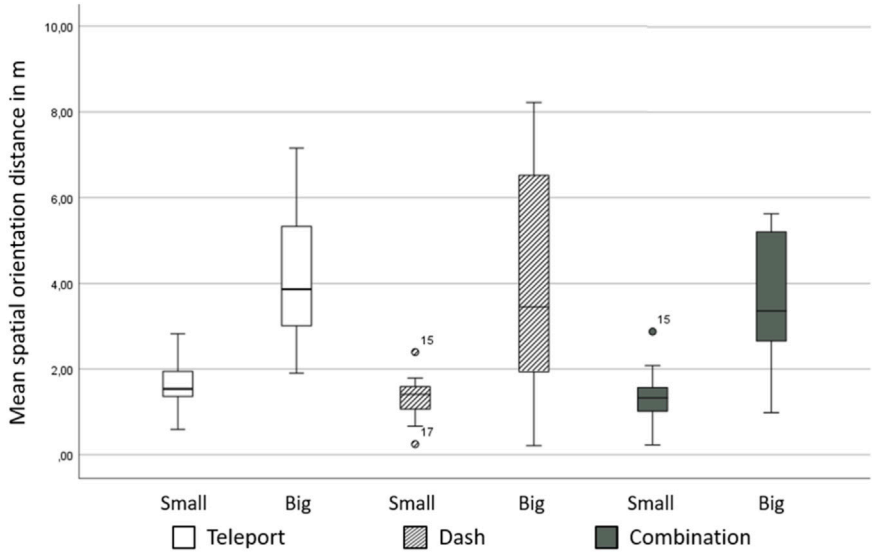


FIGURE 4
Mean spatial orientation distance (distance between the assumed and the actual start position) in m.

significantly higher in the small triangle condition than in the big triangle condition ($p < 0.001$). There was no significant interaction effect between the locomotion type and the triangle size observed, $F(2, 34) = 0.06$, $p = 0.939$.

## 3.2 Spatial orientation distance

Our analysis focused on the distance between the assumed and the actual starting position. A smaller deviation corresponds to a better spatial orientation. Looking at the results (see Figure 4) separately for the two triangle sizes, for big triangles the combination condition shows the smallest deviations (M = 3.60 (SD = 1.53)), followed by the dash condition (M = 4.10 (SD = 2.52)) and the teleport condition (M = 4.17 (SD = 1.59)) with the largest deviations. The smallest deviation in the trails with small triangles was shown for the dash condition (M = 1.33 (SD = 0.50)), followed by the combination condition (M = 1.34 (SD = 0.59)) and the teleport condition (M = 1.58 (SD = 0.56)). Mauchly's test indicated that the assumption of sphericity had not been violated for locomotion type, $\chi 2\ (2) = 4.27$, $p = 0.118$. A repeated-measures ANOVA did not reveal a significant effect between th*e spatial orientation distance and the type of locomotion, F (2, 34) = 1.83, $p > 0.05$, $\eta P^2 = 0.10$, 95 %-KI [0.00, 0.24]. Nevertheless, there was a significant large main effect of the triangle size on the spatial orientation distance, F (1, 17) = 52.69, $\eta P^2 = 0.76$. The pairwise* comparisons revealed that the spatial orientation distance was significantly more accurate in the small triangle condition than in the big triangle condition ($p < 0.001$). Our analysis could not detect a significant interaction effect between the locomotion type and the triangle size, $F(2, 34) = 0.88$, $p = 0.426$, $\eta P^2 = 0.05$, 95 %-KI [0.00, 0.20]. Additionally, we examined the correlation between the two dependent variables. We could not detect a significant correlation between participants' average spatial orientation ratings and average distance errors, $r\ (16) = -0.105$, $p = 0.678$, 95 %-KI [−0.54, 0.41]. A Spearman rank correlation yielded a similar result, $r_s\ (16) = -0.073$, $p = 0.773$, 95 %-KI [−0.55, 0.47]. Thus, participants' subjective orientation ratings did not reliably predict their objective performance.

## 3.3 Cognitive load

With regard to the cognitive load, the dash condition achieved the best values for small triangles ($M = 4.38$ ($SD = 1.70$)) whereas the combination of teleport and dash was perceived as the most stressful for big triangles ($M = 5.19$ ($SD = 1.47$)). Mauchly's test indicated that the assumption of sphericity had been violated for locomotion type, $\chi 2\ (2) = 11.19$, $p < 0.01$. A repeated-measures ANOVA with Greenhouse-Geisser correction did not reveal a significant effect between cognitive load and the type of locomotion, F (1.33, 22.62) = 0.47, $p > 0.05$, $\eta P^2 = 0.03$, 95 %-KI [0.00, 0.22]. But we found a significant large main effect of the triangle size on the cognitive load, $F(1, 17) = 6.89$, $\eta P^2 = 0.29$. The pairwise comparisons revealed that the cognitive load was significantly lower in the small triangle condition than in the big triangle condition ($p < 0.05$). Further, we could not detect a significant interaction effect between the locomotion type and the triangle size, $F(2, 34) = 1.61$, $p = 0.215$, $\eta P^2 = 0.09$, 95 %-KI [0.00, 0.26].

## 3.4 Cybersickness

Baseline-corrected cybersickness scores were computed by subtracting the pre-experiment baseline from each post-block rating, with positive values indicating an increase and negative values indicating a decrease in perceived cybersickness. Since both, the Kolmogorov-Smirnov test and Shapiro-Wilk test, as well as the observed skewness and kurtosis of the data, identified a violation of the normal distribution, non-parametric methods

were used to further analyze the data. A non-parametric factorial analysis based on the aligned rank transform was conducted to examine the effects of locomotion type and triangle size on cybersickness. The analysis did not reveal a significant main effect of locomotion type, $F$ (2, 85) = 0.11, $p$ = 0.896, nor a significant main effect of triangle size, $F$ (1, 85) = 3.04, $p$ = 0.085, and significant interaction between locomotion type and triangle size, $F$ (2, 85) = 0.14, $p$ = 0.871.

# 4 Discussion

We investigated whether the level of continuous locomotion influences spatial updating in VR when physical movement cues are absent. Additionally, perceived spatial orientation, cognitive load, and cybersickness were evaluated. Unfortunately, it was not possible to recruit a sufficient number of participants, and a follow-up data collection was not possible. The limited sample size reduces the statistical power of the analyses and restricts the generalizability of the results. We therefore present preliminary findings that may serve as a basis for further investigation but should not be overinterpreted. Replication with a larger sample is strongly recommended to verify the observed trends and ensure the robustness of the conclusions. Our results regarding cybersickness show that neither the locomotion form nor the size of the triangles has a significant influence on cybersickness. Although no statistically significant differences were observed, the descriptive statistics suggest a numerical trend toward slightly lower cybersickness scores for teleport compared to dash locomotion. Despite the absence of significant effects, this descriptive pattern is in line with the results of Paris et al. (2019), and Bozgeyikli et al. (2019) still show a slight advantage in cybersickness for teleport over continuous locomotion methods. However, because of the very low cybersickness scores it can be concluded that almost no cybersickness symptoms occurred in our study. The lack of cybersickness symptoms can be explained in various ways: On the one hand, the speed of the continuous movement could simply have been too low to cause corresponding symptoms or to produce a noticeable vection at all. Another reason, which is closely related to the first, could be that the sparse environment could have ensured that the participants generally felt little vection, as the visual stimuli were too sparse for this.

With regard to cognitive load, a mean load was measured for all locomotion methods as well as for all triangle sizes, which did not differ significantly between the conditions. In addition, there was no interaction effect, meaning that the effect of the locomotion type on cognitive load does not vary depending on the size of the triangle. The reasons for these findings could lie in several factors. First, the sample size (N = 18) may not provide sufficient statistical power to detect subtle effects. Additionally, cognitive load was assessed using only a single item for overall cognitive load. The absence of time pressure likely reduced cognitive load, as participants could pause and orient themselves. This is reflected in the time measurements: “dash” took the longest, despite theoretically imposing the lowest cognitive load. Comparisons are complicated, however, because “teleport” did not involve traversal time, unlike “dash” and “combination.”

We investigated both subjective and actual spatial orientation, with the latter measured by the difference between the perceived and actual starting positions. On average, participants in all conditions stated that they felt moderately well oriented. For both subjective and actual orientation, participants performed significantly better in the small triangles than in the big triangles. In addition, our findings showed no interaction effect between locomotion type and triangle size, which means that the effect of the locomotion type on spatial orientation rating does not vary depending on the size of the triangle. Participants’ subjective ratings of their spatial orientation indicated that they felt most oriented in the dash condition, followed by the combination condition, and least oriented in the teleport condition. The objectively measured deviation from the target position also showed that the teleport condition performed slightly worse, regardless of triangle size. However, the differences between conditions were very small, suggesting that these variations were likely not noticeable to participants. Interestingly, participants’ subjective spatial orientation ratings did not significantly correlate with their distance errors. This suggests that feeling oriented does not necessarily translate to more accurate movements. Several factors may explain this dissociation, including the coarse granularity of the 7-point rating scale, individual differences in compensatory strategies, and the relatively small sample size, which limits statistical power. Future studies could include more sensitive or objective measures of spatial orientation to better capture the relationship with performance.

Although the performance of the participants in the condition with the big triangles was worse than in the condition with the small triangles, there was no significant difference between the locomotion types in any of the conditions, neither for the estimated nor for the actual spatial orientation. The fact that the type of locomotion had almost no influence and the fact that the participants achieved relatively small deviations (e.g., compared to (Breitkreutz et al., 2022)) suggests that the distant landmarks were completely sufficient for good orientation performance. It can therefore be assumed that the anticipated advantage of the forms of movement with a continuous movement component due to the landmarks had no or minimal influence on the spatial orientation.

Two key statements can be derived from our results for our tested scenario: First, the type of locomotion and the size of the triangles have no significant influence on the perceived cybersickness. Second, the type of locomotion has no significant influence on the orientation performance for both triangle sizes. These findings align with existing research and highlight that our scenario–featuring four distant landmarks, a snow-covered and an even surface – provided optimal conditions for spatial orientation and minimal cybersickness, regardless of locomotion type or the extent of continuous movement. Thus, in scenarios requiring good spatial orientation and low cybersickness, the locomotion type can be selected based on other considerations, as the choice has minimal impact on spatial orientation, cybersickness and cognitive load, under these conditions. Future research should investigate longer distances, higher speeds, richer visual environments, individual user preferences, and also the effects of performing the task while standing to optimize VR locomotion techniques and balance orientation accuracy with comfort. In addition, a limitation of the present study is that cybersickness and cognitive load were

assessed exclusively using subjective measures. Future studies should therefore complement self-report data with objective assessment methods to allow for a more comprehensive evaluation of these effects.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by the Ethics committee of the Chemnitz University of Technology. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

JB: Conceptualization, Formal Analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. PS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review and editing. AM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – review and editing. SK: Conceptualization, Data curation, Methodology, Software, Writing – review and editing. FK: Funding acquisition, Project administration, Resources, Supervision, Writing – review and editing. MD: Supervision, Writing – review and editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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