Assessing the Accuracy of Point & Teleport Locomotion with Orientation Indication for Virtual Reality using Curved Trajectories

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Figure 1: A user is teleporting herself in a Virtual Environment using the *Curved Teleport*. It allows her to teleport around an obstacle and graphically choose the orientation, which she wants to face after teleportation only by using the curved trajectory visualization with orientation indication, and without having to turn her body in the physical world.

ABSTRACT

Room-scale Virtual Reality (VR) systems have arrived in users' homes where tracked environments are set up in limited physical spaces. As most Virtual Environments (VEs) are larger than the tracked physical space, locomotion techniques are used to navigate in VEs. Currently, in recent VR games, point & teleport is the most popular locomotion technique. However, it only allows users to select the position of the teleportation and not the orientation that the user is facing after the teleport. This results in users having to manually correct their orientation after teleporting and possibly getting entangled by the cable of the headset. In this paper, we introduce and evaluate three different point & teleport techniques that enable users to specify the target orientation while teleporting. The results show that, although the three teleportation techniques with orientation indication increase the average teleportation time, they lead to a decreased need for correcting the orientation after teleportation.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Pointing**; *User studies*;

KEYWORDS

Virtual Reality, Locomotion, Teleportation, Orientation Indication, Virtual Environments, Point & Teleport

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1 INTRODUCTION

While walking naturally has been known to be the most immersive [33, 35] and least discomforting [21, 27] active locomotion technique [17] for navigating through VEs, walking naturally is challenging as VR systems have a limited tracking space. Thus, research in VR locomotion focused on creating locomotion techniques that account for these spatial mismatches between wide and spatious VEs and limited physical spaces [43].

Teleportation, especially point & teleport [11], is a very popular locomotion technique, that overcomes the problem of confined physical spaces by enabling users to teleport to selected target positions using a hand-held controller. While it has been argued that teleportation is an unnatural type of movement [10] and that users do not gain spatial knowledge of the VE when teleporting [3], combining teleportation and real walking does not lead to a mismatch of physical movement and virtual movement [25]. Traditionally, the state-of-the-art point & teleport locomotion technique uses a parabola shaped visualization for selecting the target position and does not allow for selecting the user's orientation while teleporting. Therefore, the users are required to physically turn their bodies to adjust their orientation after each teleport. However, with the currently still tethered head-mounted displays (HMDs), this can result in users getting entangled in their HMDs' cables.

To overcome this, Bozgeyikli *et al.* [11] introduced a point & teleport technique that allows users to specify their orientation while teleporting, and compared it to the traditional point & teleport technique. While their findings from a study using a maze escape task favor the traditional point & teleport approach, in this paper, we aim to revisit the idea of including orientation indication into point & teleport locomotion using a target acquisition task. This task requires users to precisely control their orientation, to compare five point & teleport techniques: two traditional point & teleport techniques (*Linear Teleport* and *Parabola Teleport*), the original orientation indication teleport by Bozgeyikli *et al.* [11] (*AngleSelect Teleport*), and two novel teleportation techniques (*Curved Teleport* and *HPCurved Teleport*) using curved trajectories to select and indicate the user's orientation after teleporting (see Figure 1).

The contribution of this paper is two-fold. First, we introduce two novel point & teleport techniques with orientation indication using curved trajectories. Second, through a controlled lab study, we evaluate the two proposed teleportation techniques and compare them with two baseline teleportation techniques and one point & teleport technique with orientation indication from the literature.

2 RELATED WORK

In this section, we provide an overview about relevant related locomotion techniques for navigating through VEs. We assign the approaches to two groups: general locomotion techniques for VEs and point & teleport locomotion.

Virtual Reality Locomotion

From walking in place [39], moving tiles [19], powered shoes [20], leaning in chairs [23], using fingers [22, 47] or controllers to simulate walking [32] - many locomotion techniques for navigating through VEs have been introduced. They all have the goals of efficiently enabling locomotion for users in VR without causing discomfort or simulator sickness [27].

As it is known that real walking is more immersive compared to other locomotion techniques [33, 35, 40], more and more locomotion techniques for navigating through VEs focused on enabling the users to walk naturally, while considering the space constraints of the physical environment. A prominent and well researched [29] example is the redirected walking technique [34] that was first introduced by Razzaque *et al.* [31]. Here users are made believe to walk a straight line but are subconsciously steered to walk in circles to make the physical space feel endless. This has been used in many demonstrations [37] and has even been validated for curved virtual paths [24] and for giving impulses with electronic muscle stimulation [1].

In contrast, step-in-place [9], tap-in-place [30], or walk-in-place [39] systems enable users to walk, while constraining them to stay in the same physical position [18]. The most prominent example is treadmill systems that are meanwhile available commercially (e.g. the Cyberith Virtualizer[1] or the Virtuix Omni[2]). However, these systems cannot meet the feeling of real walking [40, 42], require space in a user's home, and are still expensive.

Other techniques make intelligent use of the available physical space. For instance, Wilson *et al.* [44] are exploring different translational gains for moving in VEs to make a room seem larger. Another technique to trick users into believing that their interaction space is much larger, is the impossible spaces technique [38]. Here, multiple virtual rooms have self-overlapping architecture using the same physical space multiple times. This technique can be used to generate dynamic layouts for infinite walking in VEs [41] and further be improved by predicting a user's walking direction [28].

Similar to a minimap navigation, the Worlds in Miniature (WIM) locomotion technique that was introduced by Stoakley *et al.* [36] in 1995 lets users move in a miniature model of the VE without motion sickness [4]. It was equipped

[1]Cyberith Virtualizer - https://www.cyberith.com/ (last access 09-21-2018)
[2]Virtuix Omni - www.virtuix.com/ (last access 09-21-2018)

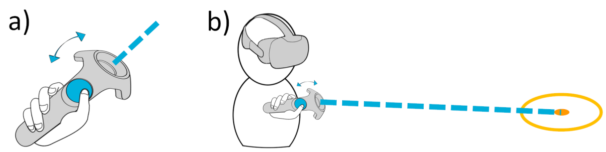

Figure 2: A user is using the *Linear Teleport* to move onto a target. The orientation that the user is facing is the forward vector of the straight teleport line.

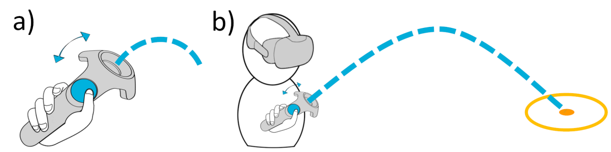

Figure 3: The *Parabola Teleport* uses a parabola shaped visualization to indicate the target position of the teleport. After the teleport, users face the forward vector of the teleport.

with scaling and scrolling to become more scalable [45]. Recently, similar to our approach, Elvezio *et al.* [12] combined the WIM locomotion technique with enabling the user to adjust their orientation through choosing head pitch and yaw before the teleportation.

Summing up, previous related approaches for locomotion in VR focused on walking-in-place, redirected walking, creating overlapping VEs, or using a minimap navigation. A comprehensive overview about VR locomotion techniques is also presented by Boletsis [7].

Point & Teleport Locomotion

The point & teleport locomotion technique is implemented in more and more state-of-the-art VR games. Although, with the proliferation of room-scale VR systems this locomotion technique only recently gained popularity, it was already in 1997, when Bowman *et al.* [10] found that pointing-based techniques outperform gaze-based locomotion techniques. In the VR literature, Bozgeyikli *et al.* [11] were the first in 2016 to introduce the point & teleport technique. They compare it to a traditional walk-in-place and joystick based movement.

However, teleportation has been used for enhancing locomotion in VEs previously. One example is Freitag *et al.* [13], who used teleportation after users walk through interactive portals in a CAVE system. Using the teleportation, the users are reoriented in the VE. Another example using teleportation is the jumper metaphor [8], which enables users to combine real walking and teleporting to a predicted position jumping.

Recently, point & teleport locomotion became more popular and was included in recent research. Frommel *et al.* [14] investigate the effects of different controller-based locomotion techniques on the user. They conclude that a free point & teleport technique leads to the least discomfort. Further, Xu *et al.* [46] compare the point & teleport locomotion technique to joystick and walk-in-place locomotion. They could not find a significant difference in the spacial knowledge gain between the conditions.

However also new locomotion techniques using point & teleport were recently introduced. Bhandari *et al.* [5] present Dash, which lets users estimate the travelled distance during point & teleport locomotion. Further, Liu *et al.* [26] introduced redirected teleportation, which spawns a portal in different directions to prevent users from walking into walls.

Interestingly and most relevant for our paper, Bozgeyikli *et al.* [11] added an orientation indication that lets the users control the orientation which they want to face after the teleport. However, after an initial proof-of-concept study [11], the teleportation with orientation selection did not lead to a better performance compared to the traditional point & teleport locomotion technique without orientation indication. The authors even conclude that *"the direction indication degraded the user experience"*. Despite Bozgeyikli *et al.* [11]'s findings, which we consider important and valid, orientation indication was only evaluated using a maze-task that did not require users to precisely control their orientation. Thus, we claim that the full potential of using orientation indication in point & teleport locomotion is still unexplored.

Summing up, although point & teleport with orientation selection has been suggested in previous research [11], its potentials have not been analyzed in a study that requires users to accurately use orientation indication for reaching targets precisely. In this paper, we re-implement the point & teleport technique with orientation indication by Bozgeyikli *et al.* and introduce two new point & teleport techniques with orientation indication using a curved teleportation trajectory. Finally, through a user study, we compare these three point & teleport techniques with orientation indication with two traditional teleportation techniques without orientation indication.

3 POINT & TELEPORT TECHNIQUES

In order to evaluate the different VR locomotion point & teleport techniques, we implemented three teleportation techniques that were inspired by both state-of-the-art systems and the literature. Additionally, we implemented two novel teleportation techniques. All teleportation techniques are implemented in Unity version 2018.1.3f1 using an HTC Vive VR system. For our hardware setup, we further use deluxe audio headstraps and a leather VR Facecover for hygienic reasons.

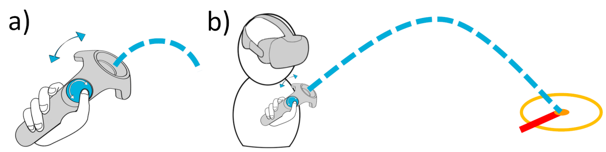

Figure 4: The *AngleSelect Teleport* uses a parabola visualization to show the user the target position. Further it uses an orientation indicator that lets the user select the orientation that the user is facing after the teleport.

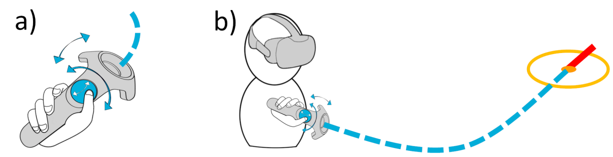

Figure 5: The *Curved Teleport* visualizes the trajectory of the teleportation in a curved line. The orientation that the user is facing at the target location can be influenced by adjusting the steepness of the curve.

Linear Teleport

Our first and most basic teleportation method is the *Linear Teleport*. Using the *Linear Teleport*, the user can point at a target location using a straight line as a visual representation for the teleport destination. The *Linear Teleport* is depicted in Figure 2.

The *Linear Teleport* on our HTC Vive controller is implemented as follows: Once the user presses and holds the touchpad on the controller, the *Linear Teleport* is active. While the *Linear Teleport* is active, the user can point at a target location using its straight line visualization. The target position is visualized with an orange circle that is displayed on the ground (see Figure 2). When the user releases the touchpad on the controller, the user is teleported to the target location. The orientation in which the user is facing after the teleport is the forward vector of the straight line of the *Linear Teleport*'s visualization.

Parabola Teleport

We consider the *Parabola Teleport* the most-common and state-of-the-art teleportation system as it is used in many recent VR applications (e.g. VRChat[3] or SteamVR Home[4]). A user can point at a target location like in the *Linear Teleport*, however the line that points to the target location is shaped in a parabola (see Figure 3).

A user can activate the *Parabola Teleport* by pressing and holding the touchpad on the HTC Vive controller. The system then displays a parabola to select the target. A user can further change the length of the parabola by changing the angle on the pitch axis. Holding the controller in a steeper angle will result in a steeper parabola, while holding the controller straight line will result in a straight line (as in the *Linear Teleport*). The *Parabola Teleport* also uses an orange circle for displaying the target location at the position where the parabola intersects with the ground. When a user releases the touchpad on the controller, the user will be teleported to the target location facing the forward vector of the parabola.

[3]VRChat - https://vrchat.net (last accessed 09-21-2018)
[4]SteamVR Home - https://steamcommunity.com/steamvr (last accessed 09-21-2018)

AngleSelect Teleport

The *AngleSelect Teleport* is a not very common teleportation technique that was previously introduced by Bozgeyikli *et al.* [11]. It is similar to the *Parabola Teleport*, however, it additionally lets a user select a target orientation that the user is facing after the teleport (see Figure 4).

Similar to the *Parabola Teleport*, the users can activate the *AngleSelect Teleport* by pressing the touchpad on the HTC Vive Controller and change the length of the parabola by holding the controller in a different angle on the pitch axis. Additionally, by moving the finger on the round touchpad, a user can select the orientation which should be faced after the teleport. The target location of the teleport is displayed using an orange circle. In the *AngleSelect Teleport*, the target circle is extended with a red orientation indicator, which points towards the currently selected target orientation. As soon as the user releases the touchpad, the user is teleported to the target location facing the selected orientation. This extends the state-of-the-art *Parabola Teleport* by including orientation selection into the teleport.

Curved Teleport

The *Curved Teleport* is a teleportation technique that is inspired by the attention funnel visualization by Biocca *et al.* [6]. It uses a curved shaped trajectory visualization that is similar to rotating the visualization of the *Parabola Teleport* in a 90° angle. The *Curved Teleport* lets a user combine selecting a target position and a target orientation (see Figure 5).

As the previous teleportation techniques, the *Curved Teleport* is also activated by pressing and holding the touchpad on the HTC Vive controller. However, the parameters of the parabola are controlled by moving the controller along the roll axis to adjust the steepness of the curve. Further, the users are able to adjust the length of the curve by sliding their finger on the touchpad: forward to increase the length or backwards to reduce the length. Similar to the previous teleportation methods, the target location is indicated by an orange circle and a red orientation indicator pointing towards the forward direction of the curve. In contrast to the

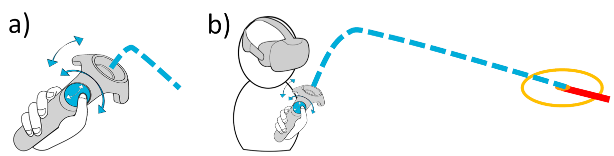

Figure 6: The visualization of the *HPCurved Teleport* first uses a parabola that behaves like a state-of-the-art *Parabola Teleport*, but at the high point of the parabola turns into a *Curved Teleport* that lets the users chose the target orientation.

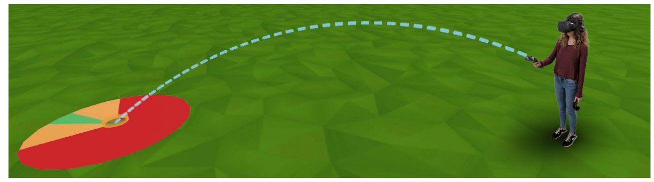

Figure 7: We used round targets in our accuracy study. The direction of the target is indicated by the green target area and supported by the yellow target area. The rest of the target is colored in red indicating the wrong direction. In this screenshot of our accuracy study, the participant is using the *Parabola Teleport*. (Picture of participant added for clarity).

AngleSelect Teleport, in the *Curved Teleport* this red orientation indicator cannot be adjusted and is only there to display the forward direction to the user. The target orientation can be manipulated by adjusting the steepness of the curved trajectory. Finally, when the user releases the touchpad, the user is teleported to the selected position facing the orientation that is shown by the red indicator.

HighPointCurved Teleport

The *HighPointCurved Teleport* (further abbreviated as *HPCurved Teleport*) is a mix between the *Parabola Teleport* and the *Curved Teleport*. Until the parabola's high point, its visualization is identical to the *Parabola Teleport*. However, after the high point of the parabola, the visualization turns into a curve just like in the *Curved Teleport* (see Figure 6).

The users can activate the *HPCurved Teleport* by pressing and holding the touchpad on the HTC Vive controller. In contrast to the *Curved Teleport* or the *Parabola Teleport*, in the *HPCurved Teleport* the users can adjust two parameters while doing the teleport. Using the roll axis, the users can alter the steepness of the curve that it has after the high point. A higher roll movement results in a higher steepness of the curve. Similar to the *Curved Teleport*, the users can adjust the length of the curve by sliding their finger on the touchpad forwards and backwards. The orange target indicator and the red orientation indicator are the same as in the *Curved Teleport*. Again, when the user releases the touchpad, the teleportation is performed and the user is teleported to the chosen position facing the indicated orientation.

4 EVALUATION

We conduct a user study to evaluate the five different point & teleport methods for VR. By conducting this study, we aim to proof or disproof the following five hypotheses:

- $\mathbf{H}_0$ The different teleportation methods in combination with natural walking do not influence the participants' ability to reach target positions and target orientations.
- $\mathbf{H}_1$ The different teleportation methods lead to a different amount of using natural walking for correcting the target position.
- $\mathbf{H}_2$ The teleportation methods with orientation indication lead to a lower amount of using natural walking for correcting the target angle .
- $\mathbf{H}_3$ Teleportation methods with orientation indication require more time to use.
- $\mathbf{H}_4$ Curved trajectories induce an increased perceived cognitive load compared to parabola-shaped trajectories.

Design

We designed the user study following a repeated measures design with the used teleportation method as only independent variable with five levels (*Linear Teleport*, *Parabola Teleport*, *AngleSelect Teleport*, *Curved Teleport* and *HPCurved Teleport*). As dependent variables, we measured the distance to the target (d_{target}), the physical distance correction using natural walking after the teleport ($d_{corrected}$), the rotation offset to the target angle (α_{target}), the physical orientation correction using natural walking after the teleport ($\alpha_{corrected}$), the average time needed to teleport ($t_{teleport}$), the time spent for using natural walking to correct the position and orientation after the last teleport ($t_{corrected}$), the amount of teleports needed ($n_{teleports}$), and the perceived cognitive load for each teleportation method using the Raw NASA Task Load Index (RTLX) [15] score. To avoid learning effects, we used a 5×5 Balanced Latin Square to counterbalance the conditions.

We defined d_{target} as the distance from the position of the user's HMD to the middle of the target and $d_{corrected}$ as the distance that the user corrected by walking naturally after the last teleport was made. Further, α_{target} is defined as the angle between the forward vector of the participant's HMD and the target's direction vector. Finally, we defined $\alpha_{corrected}$ as the angle, that the participant corrected using natural walking after the last teleport was made.

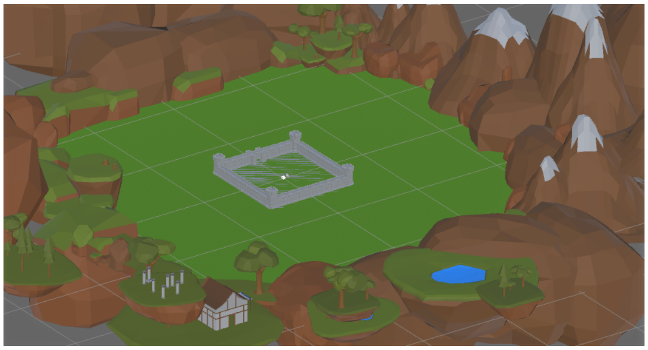

Figure 8: The VE that we created as the environment for conducting the study. The castle in the middle of the environment is the tutorial area, where participants can practice the teleportation method before starting the study. Once participants leave the tutorial castle, it disappears and becomes a green lawn area.

Apparatus and Task

We created a VE, which consists of a green lawn area that is limited by rocks around it. At the beginning of each teleportation method, the user starts in a castle that represents a tutorial and training environment (see Figure 8). In this tutorial castle the users can try the current teleportation method until they feel comfortable using the teleportation method. Once the users teleport out of the castle, the castle disappears and our VE starts displaying the target acquisition task. Our VE spawns targets on the lawn in a distance range from 3m-10.5m away from the user and an angle of 10° from the last target. The rotation of the targets is randomly assigned from a pool of 50 available rotations, making sure that all rotations were used. The targets have a diameter of 2.5m. We specified the target direction that the user should face using a green color with a 20° beam width that is supported by a yellow area having a 100° beam width. A graphical representation of the targets we used in the study can be seen in Figure 7. It is ensured that no targets are spawned outside the lawn area of the VE and that all targets are reachable. As a task, we defined that a user has to reach and confirm 50 targets. A target is confirmed by pressing the trigger button on the HTC Vive controller. We started counting $t_{teleport}$ when the user initiated the first teleport of the current target. Therefore, the time it takes the user to visually locate the next target can be neglected.

Procedure

Before the Study. After welcoming the participants and explaining the aim of the study, we told the participants that the data is anonymized and that the position and accuracy of the teleport will be recorded. However, we did not fully disclose all dependent variables to the participants (especially not the physical movement and correction variables), as this might have influenced the participants' behavior. Once the participants agreed to take part in the study, we started with asking them to fill in a consent form and a demographic questionnaire. After that, we equipped the participants with the HTC Vive and started our VE. To get familiar with the VE and the mechanism to confirm the targets, we always started with 10 targets using the baseline Linear Teleport.

Study. After the participants were familiar with the system, we switched the teleportation method to the current condition according to a Balanced Latin Square randomization. Again, the participants started in the tutorial castle to get familiar with the current teleportation method. When the participants felt familiar with the current teleportation method, they left the castle and started moving towards the designated targets. Once the participants teleported onto a target, the participants were able to adjust the position and orientation by moving or turning naturally. However, we told the participants to use this adjustment through natural walking only as a secondary option. As a first priority, they were instructed to use the orientation indication mechanism of the current teleportation method (if applicable). After the participants reached and confirmed all 50 targets, we removed their headset again and asked them to fill in a NASA-TLX questionnaire [15]. Afterwards, we asked them to provide comments about the current teleportation method. We repeated this procedure for all five teleportation methods.

After the Study. After completing all five conditions of the user study, we asked the participants for additional qualitative feedback through a semi-structured interview.

Participants

For our user study, we recruited 20 participants (8 female, 12 male) with an age range between 21 and 35 years ($M = 26.5$, $SD = 4.45$). All participants were students or employees of our university with different majors. Considering the previous VR experience of the participants, 11 participants stated that they had very little experience, 7 participants stated that they had medium VR experience, and 3 identified themselves as VR experts. All participants took part in the study voluntarily. We did not provide any compensation for participating in the user study.

Results

We statistically compared d_{target}, $d_{corrected}$, α_{target}, $\alpha_{corrected}$, $t_{teleport}$, $t_{corrected}$, $n_{teleports}$, and the RTLX score between the five teleportation methods using a one-way repeated measures ANOVA test. Mauchly's test showed that the sphericity assumption was violated for $\alpha_{corrected}$ ($\chi^2(9) = 39.731$, $p < .001$), $t_{teleport}$ ($\chi^2(9) = 21.793$, $p = .01$), $t_{corrected}$ ($\chi^2(9) = 45.403$, $p < .001$) and RTLX ($\chi^2(9) = 28.439$,

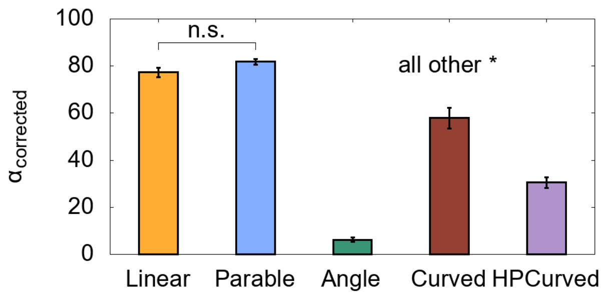

Figure 9: The average angle $\alpha_{corrected}$ that was corrected by the participants using each teleportation method. All error bars indicate the standard error. All conditions are significantly different, except the two baseline conditions (indicated with *n.s.*).

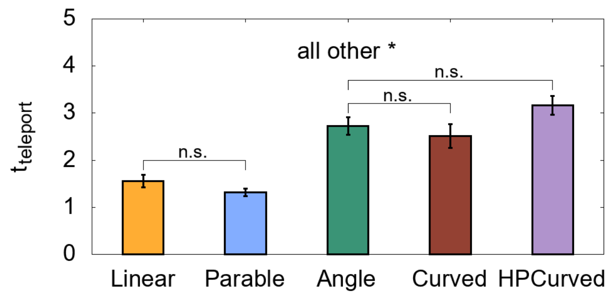

Figure 10: The average time that participants took to teleport $t_{teleport}$ using each teleportation method. All error bars indicate the standard error. All teleportation methods were significantly different, except the ones indicated with *n.s.*

$p < .001$). Therefore, we used the Greenhouse-Geisser correction to adjust the degrees of freedom ($\epsilon = .497$ for $\alpha_{corrected}$, $\epsilon = .829$ for $t_{teleport}$, $\epsilon = .49$ for $t_{corrected}$ and $\epsilon = .676$ for the RTLX score). We further used the Bonferroni correction for all post-hoc tests, which is a pessimistic correction to reduce the inflation of the type-I error.

The average distance to the target, d_{target}, for according to the teleportation methods was the following: *AngleSelect Teleport* (M = 16.89cm, SD = 5.20cm), *Parabola Teleport* (M = 17.57cm, SD = 5.46cm), *HPCurved Teleport* (M = 18.37cm, SD = 4.54cm), *Linear Teleport* (M = 19.3cm, SD = 6.31cm), and *Curved Teleport* (M = 21.55cm, SD = 8.46cm). A repeated measures ANOVA revealed a significant difference between the conditions $F(4, 76) = 2.572$, $p = .044$. However, post-hoc pairwise comparisons did not show any significant effect between the different teleportation methods. The effect size estimate shows a medium effect ($\eta^2 = .119$)

Considering the distance that the users corrected manually after using the teleport, $d_{corrected}$, the teleportation methods led to the following amount of manual correction: *Curved Teleport* (M = 3.79cm, SD = 3.47cm), *AngleSelect Teleport* (M = 4.86cm, SD = 8.68cm), *Parabola Teleport* (M = 5.08cm, SD = 4.64cm), *HPCurved Teleport* (M = 5.29cm, SD = 4.85cm), and *Linear Teleport* (M = 6.7cm, SD = 6.05cm). However, a repeated measures ANOVA could not find a significant difference regarding the $d_{corrected}$ between the teleportation methods ($p > 0.05$). The effect size estimate shows a small effect ($\eta^2 = .034$).

For the rotation offset to the target angle, α_{target}, the teleportation methods performed the following: *Parabola Teleport* (M = 4.86°, SD = 2.50°), *Linear Teleport* (M = 5.36°, SD = 1.76°), *Curved Teleport* (M = 5.56, SD= 2.49°), *AngleSelect Teleport* (M = 5.62°, SD = 2.64°), and *HPCurved Teleport* (M = 5.64°, SD = 2.67°). A repeated measures ANOVA could not find a significant difference regarding α_{target} between the teleportation methods ($p > 0.05$). The effect size estimate shows a small effect ($\eta^2 = .051$).

Considering the angle that the users manually corrected after the teleport, $\alpha_{corrected}$, the teleportation methods performed the following: *AngleSelect Teleport* (M = 6.23°, SD = 4.30°), *HPCurved Teleport* (M = 30.46°, SD = 10.5°) and the *Curved Teleport* (M = 57.96°, SD = 19.59°). The two baseline conditions led to an increased manual angle correction: *Linear Teleport* (M = 77.26°, SD = 8.59°) and *Parabola Teleport* (M = 81.82°, SD = 5.2°). A repeated measures ANOVA revealed a significant difference between the conditions $F(1.809, 34.377) = 168.532$, $p < .001$. A post-hoc test shows significant differences between all conditions except the two baseline conditions *Linear Teleport* and *Parabola Teleport* (all $p < 0.05$). The results are also depicted in Figure 9.

Analyzing the time the users spend per teleport, $t_{teleport}$, the two baseline conditions led to the lowest amount of time spend per teleport: *Parabola Teleport* (M = 1.31s, SD = 0.36s) and *Linear Teleport* (M = 1.56s, SD = 0.60s). The rotation-aware teleportation methods led to a higher $t_{teleport}$: *Curved Teleport* (M = 2.51s, SD = 1.13s), *AngleSelect Teleport* (M = 2.73s, SD = 0.86s), and *HPCurved Teleport* (M = 3.16s, SD = 0.89s). A repeated measures ANOVA revealed a significant difference between the conditions $F(2.787, 52.951) = 46.108$, $p < .001$. Post-hoc pairwise comparisons revealed a significant difference (all $p < 0.05$) between all teleportation methods except the two baseline methods *Linear Teleport* vs. *Parabola Teleport*, *AngleSelect Teleport* vs. *Curved Teleport*, and *AngleSelect Teleport* vs. *HPCurved Teleport*. The results are also depicted in Figure 10.

Regarding the time the users took to physically correct their position after their last teleport, $t_{corrected}$, the teleportation methods led to the following times: *AngleSelect Teleport* (M = 1.61s, SD = 0.59s), *HPCurved Teleport* (M = 1.69s, SD = 0.38s), *Linear Teleport* (M = 1.94s, SD = 0.34s), *Parabola Teleport* (M = 1.99s, SD = 0.54s), and *Curved*

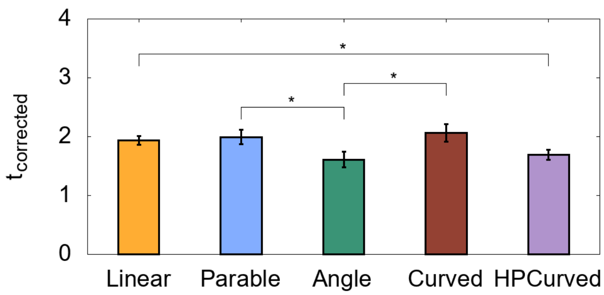

Figure 11: The average time that participants took to correct their position $t_{corrected}$ using natural walking for each teleportation method. All error bars indicate the standard error. The asterisk (*) indicates a statistically significant difference between the teleportation methods.

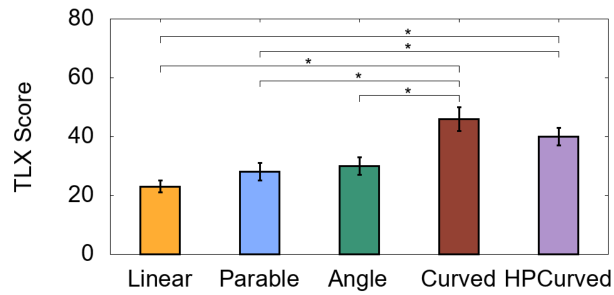

Figure 12: The NASA-TLX scores of the VR locomotion techniques that were assessed in the user study. All error bars indicate the standard error. The asterisk (*) indicates a significant difference between the locomotion techniques.

Teleport ($M = 2.07$s, $SD = 0.67$s). A repeated measures ANOVA revealed a significant difference between the conditions $F(1.787, 33.95) = 8.171$, $p < .001$. A post-hoc test using pairwise comparisons revealed a significant difference between *Linear Teleport* vs. *HPCurved Teleport*, *Parabola Teleport* vs. *AngleSelect Teleport*, and *AngleSelect Teleport* vs. *Curved Teleport Teleport* (all $p < 0.05$). The results are also depicted in Figure 11.

Lastly, considering the average number of teleports that were needed per target according to each teleportation method, $n_{teleports}$, the methods performed the following: The *Linear Teleport* (M=1.17, SD=0.23), *Parabola Teleport* (M=1.08, SD=0.09), *AngleSelect Teleport* (M=1.13, SD= 0.13), *Curved Teleport* (M=1.1, SD=0.13), and the *HPCurved Teleport* (M=1.11, SD=0.15). A one-way repeated measures ANOVA did not find any significant effect between the teleport methods.

Regarding the RTLX score measuring the perceived cognitive load, the teleportation methods performed the following: *Linear Teleport* ($M = 23.9$, $SD = 12.23$), *Parabola Teleport* ($M = 28.05$, $SD = 15.24$), *AngleSelect Teleport* ($M = 30.15$, $SD = 14.12$), *HPCurved Teleport* ($M = 40.55$, $SD = 16.94$), and *Curved Teleport* ($M = 46.15$, $SD = 18.56$). A repeated measures ANOVA revealed a significant difference between the conditions $F(2.351, 44.664) = 13.071$, $p < .001$. The post-hoc test showed a significant difference (all $p < .05$) between the *Curved Teleport* vs. the *Linear Teleport*, *Parabola Teleport*, and the *Angle Teleport*. Further, between the *HPCurved Teleport* vs. the *Linear Teleport* and the *Parabola Teleport*. The results are depicted graphically in Figure 12.

Qualitative Feedback

During our user study and through a semi-structured interview after the study, we further collected qualitative feedback about the five teleportation techniques.

The participants generally liked all point & teleport locomotion techniques. Especially the novel techniques were popular: the *Curved Teleport* and the *HPCurved Teleport “felt natural”* (P1), *“were fun”* (P15) and *“the way they work [was perceived as] fancy”* (P14). Participants enjoyed the new features of the teleportation methods. One participant stated that *“the HPCurved Teleport was interesting, especially when making short distance teleports with a lot of rotation”* (P2). However, also the other teleportation techniques were perceived well. P5 stated that *“the Parabola Teleport and AngleSelect Teleport felt simple and intuitive to use”*.

Considering the baseline teleportation techniques, two participants stated that *“[they] preferred the Linear Teleport as it was very easy to use”* (P6, P15). However, another participant stated that *“there was no difference between the Linear Teleport and the Parabola Teleport”* (P9). Three participants (P9, P16, P17) preferred the *AngleSelect Teleport* over other teleportation techniques. A user stated that *“[he] liked the AngleSelect Teleport, but [he] took longer to use it”* (P9). P17 enjoyed the novel features as *“[she] likes that with the AngleSelect Teleport a 180° turn becomes possible”*. Further, another user stated that *“[he] likes using the AngleSelect Teleport, as [he] does not need to move that much in the physical world anymore”* (P18).

Considering the design of the experimental environment, one participant (P1) mentioned, that she would have preferred it when the targets would have spawned directly in front of her instead of the 10 degrees that was our spawning radius. Four participants had problems with the cable of the HTC Vive. Two participants stated that *“[they] needed to move the HTC Vive cable as it was in the way”* (P3, P12). Another two stated that *“[they] got entangled in the HTC Vive cable”* (P8, P13). Interestingly, the qualitative feedback also revealed that *“using the HPCurved, Curved, and AngleSelect Teleport, [users] completely lose track of the orientation in the physical world”* (P11, P12).

5 DISCUSSION

In this section, we discuss the findings of the user study according to the previously postulated hypotheses H_0–H_4.

Based on the results of our user study, we could not disprove the null hypothesis H_0, as we could not find a significant difference in the distance offset d_{target} and orientation offset α_{target}. Thus, we could not find a difference in the five teleportation methods regarding their influence on the participants' ability to reach target positions and target orientations. For designers of VR locomotion techniques, this means that when users are given the possibility to walk naturally and use teleportation with or without orientation indication, we could not find a difference in the accuracy.

Considering H_1, which states that the five different teleportation methods lead to a different amount of using natural walking to correct the target position, we used two dependent variables to support or disprove the hypothesis: the distance, that the participants corrected using natural walking after using each teleportation method ($d_{corrected}$), and the time it took them to use natural walking to correct their position and orientation ($t_{corrected}$). While $d_{corrected}$ did not reveal any significant difference between the teleportation methods, $t_{corrected}$ revealed interesting significant insights. For the *AngleSelect Teleport*, $t_{corrected}$ was significantly lower than the baseline *Parabola Teleport* and the *Curved Teleport*. Also the *HPCurved Teleport* required a significantly lower $t_{corrected}$ than the baseline *Linear Teleport*. Interestingly, although we could not draw a conclusion from $d_{corrected}$, we identified a slight advantage in $t_{corrected}$ for the *AngleSelect Teleport* and the *HPCurved Teleport*. Interestingly, this benefit was not reported in related work [11]. For designers of VR environments, this has interesting implications. When designing environments where users need to change their orientation very often (e.g. when action is happening from multiple sides, or a user has to navigate through a maze) using a teleportation method with orientation indication, the users will be able to navigate faster.

We could very clearly confirm H_2, which states that teleportation methods with orientation indication lead to a lower need to use natural walking for correcting the target orientation. The results of our study clearly showed that there is a significant difference in $\alpha_{corrected}$ between all teleportation methods with orientation indication compared to both baseline teleportation methods without orientation indication. Interestingly, the results also revealed a significant difference between the *AngleSelect Teleport* and both *Curved Teleport* and *HPCurved Teleport*. This shows that the original *AngleSelect Teleport* as introduced by Bozgeyikli *et al.* [11] is superior in terms of selecting the orientation accuracy compared to guiding users with an attention funnel [6] while teleporting. The take-away message for designers of VR environments should be to implement an *AngleSelect Teleport* as the teleportation method with orientation indication.

In our hypothesis H_3, we assumed that the possibility to select a target orientation will also result in a higher time to use the teleports. We could confirm this hypothesis, as the $t_{teleport}$ was significantly higher for each teleport with orientation indication compared to the two baseline teleports without orientation indication. This is in contrast to related work [11], which did not find a significant difference between the teleportation with and without orientation indication. Interestingly, there was a significant benefit for the *Curved Teleport* compared to the *HPCurved Teleport* regarding $t_{teleport}$. This shows that participants could use the *Curved Teleport* faster compared to the *HPCurved Teleport*. Further, we could not find a difference between the conditions regarding $n_{teleports}$, the amount of teleports that were used to reach a target. Designers of future VR environments have to consider that providing the user with a teleport with orientation indication in leads to a higher time that users need for teleporting.

Finally, we could almost completely confirm H_4, which postulated that teleportation methods with curved trajectories induce an increased perceived cognitive load compared to parabola shaped trajectories. Regarding the RTLX score, we found that the three teleportation methods using a non-curved trajectory (*Linear Teleport*, *Parabola Teleport*, and *AngleSelect Teleport*) lead to a significantly lower perceived cognitive load than the *Curved Teleport*. However, we could not find a significant difference between the *AngleSelect Teleport* and the *HPCurved Teleport*. The take away message for designers of VR environments is to rather use parabola shaped trajectories for indicating the teleportation paths than using curved trajectories as the latter lead to an increase in the perceived cognitive load.

In addition to the hypotheses, we could (similarly to related work [11]) confirm that the three teleportation techniques with orientation indication lead to users losing track of the VE's orientation in relation to the orientation of the physical environment. This has interesting implications for further research in the areas of haptic retargeting (cf. [2]), redirected teleportation [26], and normal walking paired with teleportation (e.g. with impossible spaces). Considering haptic retargeting, after a teleport, the VE could be re-aligned in a way that newly created virtual objects overlay existing physical objects to create haptic sensations (cf. [16]). Further, when users reach the end of the physical tracking environment, the VE could require the users to use a teleport and change the orientation of the VE while teleporting, instead of requiring the user to enter portals at fixed positions [26, 48], or freezing the world until users turned around [43]. This finding could be leveraged in future work to further improve point & teleport locomotion for navigating in VEs.

6 LIMITATIONS

It has to be mentioned that our study design for comparing the teleportation methods with each other comes with a few limitations. In our apparatus and the design of the teleportation methods, we display the directional indicators on the floor. As the teleportation methods traditionally require the user to look at the intersection of the teleportation visualization and game world (in our game world - the floor), we chose to also present the directional indicators on the floor. We want to acknowledge that displaying the directional indicators at another position, e.g. in the air in front of the user, might have yielded different results. Further, we want to point out that the task that was used in the study was a target acquisition task that required the user to accurately teleport onto a target. We did not use game mechanics to influence usage of the teleportation methods and apply ingame pressure on the users to see how they are able to use the teleportation methods in more stressful conditions. We want to acknowledge that the performance of the teleportation methods might yield different results according to different ingame situations.

7 CONCLUSION

In this paper, we introduced three teleportation techniques that enable users to specify a target orientation in addition to a target position: an *AngleSelect Teleport* that allows specifying a target orientation using a hand-held controller's touchpad, and two different teleportation techniques using curved trajectories (*Curved Teleport* and *HPCurved Teleport*). Through a user study with 20 participants, we compared the three teleportation techniques with orientation indication to two baseline teleportation techniques without orientation indication (*Linear Teleport* and *Parabola Teleport*). The results show that, although the three teleportation techniques with orientation indication increase the average teleportation time, they lead to a decreased need for correcting the orientation after teleportation. Based on this finding, we recommend that future point & teleport locomotion techniques for navigating through VEs, should provide two ways of point & teleport locomotion. First, as the default point & teleport technique, the state-of-the-art *Parabola Teleport* should be offered as it is faster to use. However, we also argue that VR games should offer an alternative point & teleport technique, which allows the users to change their orientation while teleporting, and therefore enabling users to navigate more accurately.

In future work, we want to follow up on our assumption that changing the VE's orientation while teleporting, might have interesting implications for using teleportation to subconsciously restrict users to the physically limited tracking space, while perceiving the VE to have no physical boundaries. Further, we want to analyze the teleportation methods in different game situations and stress levels.

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