SkyPort: Investigating 3D Teleportation Methods in Virtual Environments

Andrii Matviienko
matviienko@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

Florian Müller
florian.mueller@ifi.lmu.de
LMU Munich
Munich, Germany

Martin Schmitz
schmitz@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

Marco Fendrich
marco@fenbox.de
Technical University of Darmstadt
Darmstadt, Germany

Max Mühlhäuser
max@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

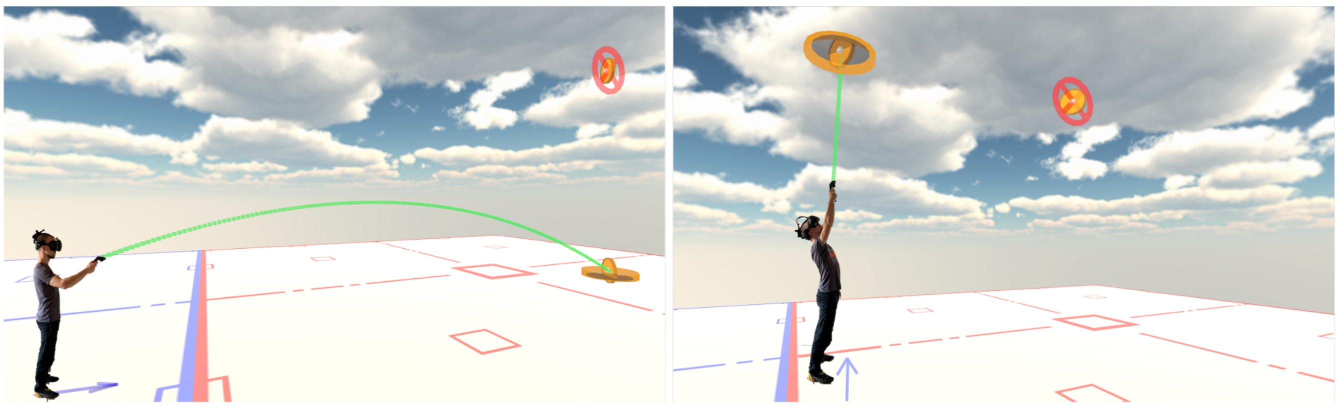

Figure 1: Two possible scenarios for teleportation in 3D space: a user is teleporting horizontally to a target using a parabolic aiming method (left) and a user is teleporting vertically to a target using a linear aiming method (right).

ABSTRACT

Teleportation has become the de facto standard of locomotion in Virtual Reality (VR) environments. However, teleportation with parabolic and linear target aiming methods is restricted to horizontal 2D planes and it is unknown how they transfer to the 3D space. In this paper, we propose six 3D teleportation methods in virtual environments based on the combination of two existing aiming methods (linear and parabolic) and three types of transitioning to a target (instant, interpolated and continuous). To investigate the performance of the proposed teleportation methods, we conducted a controlled lab experiment (N = 24) with a mid-air coin collection task to assess accuracy, efficiency and VR sickness. We discovered that the linear aiming method leads to faster and more accurate target selection. Moreover, a combination of linear aiming and instant transitioning leads to the highest efficiency and accuracy without increasing VR sickness.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**; **Empirical studies in HCI**.

KEYWORDS

virtual reality, teleportation, locomotion, virtual environments

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1 INTRODUCTION

While virtual reality environments allow for infinitely large spaces, the physical movement of the user is limited by the boundaries of the tracking space in the real world. This effectively rules out natural modes of locomotion, such as walking in VR, to cover longer distances. Researchers have attempted to address this challenge by introducing artifical locomotion techniques [1, 12, 15, 41], which typically facilitate two main types of movement in virtual environments: (1) discrete and (2) continuous. The most notable discrete locomotion technique is teleportation [9], which allows users to arbitrarily cover virtual distances in "jumps" without moving in the real world using controllers [9, 14], gates [17], or static portals [13]. Continuous locomotion, on the other hand, allows movement through virtual environments, e.g., via flying [19, 24, 34, 38, 47], independently from physical constraints and gravity compared to 2D ground-based locomotion. While continuous movement is adapted for locomotion in both 2D and 3D space, it often leads to an increased VR sickness [4, 5, 17]. On contrary, discrete movement is predominantly restricted to the horizontal 2D plane or pre-defined 2D planes (2.5D). Therefore, the question is how discrete 2D locomotion techniques can be extended to 3D space, e.g., to teleport to any point in 3D space, and how efficient they will be. Answering both questions will shed light on the most efficient way to fully explore 3D virtual environments regardless of the virtual landscape, physical constraints and gravity.

In this work, we aim to advance teleportation from the horizontal 2D plane to 3D space. For this, we focus on techniques that facilitate aiming and transitioning to a target, which have shown to influence teleportation performance on the 2D plane [14] (Figure 1). Therefore, we explore two existing aiming techniques (parabolic and linear) and three types of transitioning to a target: (1) instant, (2) interpolated (as an intermediary step between discrete and continuous movement), and (3) continuous. To investigate the efficiency of the 3D teleportation techniques in the 3D VR space, we conducted a controlled laboratory experiment (N = 24) to assess the speed and precision of the techniques, and VR sickness induced by them. We found that linear teleportation outperforms parabolic in terms of speed and number of teleportations necessary to reach a target. Moreover, the combination of linear aiming and instant transitioning leads to faster and more precise teleportation to a target without significantly inducing VR sickness.

Our main research contributions include:

- Six 3D teleportation methods in virtual environments.
- An empirical evaluation of six proposed 3D teleportation methods focused on the quick and precise target selection and reduction of VR sickness.

2 RELATED WORK

In this section, we provide an overview of the existing virtual reality locomotion techniques with a special focus on point & teleport locomotion techniques. This provides a basis for teleportation methods along horizontal and vertical planes in 3D virtual environments.

2.1 Virtual Reality Locomotion Techniques

Locomotion techniques in virtual reality (VR) cover a large spectrum: from walking in place [36], moving tiles [15] and shoes [16], leaning in chairs [20, 40], using fingers [18, 46] and controllers to simulated walking [32]. Most of them, however, fall into two main categories: (1) discrete and (2) continuous movement through virtual space. The most notable discrete locomotion technique in VR is teleportation [9]. It allows users to arbitrarily cover virtual distances in "jumps" without moving in the real world using controllers [9, 14], feet [10, 39], gates [17], or static portals [13]. Although discrete locomotion techniques are considered effective and fast, a recent empirical evaluation [6] showed that the "jumps" in the virtual environment break the users' sense of immersion and lead to eye strain.

To overcome these issues and potentially increase the level of immersion, researchers have proposed continuous locomotion techniques [8], such as redirected [3, 21, 26, 29, 35], scaled [1, 42], or in-place [7, 15, 27, 32, 36, 37] walking. All of these techniques facilitate continuous movement in virtual environments by walking on one spot or in circles. Although some of these techniques can be transferred to the 3D space, e.g., walking up the stairs [2, 25, 45] or jumping [33, 44], they still restrict the granular exploration of the complete 3D virtual space.

One of the most prominent continuous 3D locomotion techniques that addresses the aforementioned issue is 3D flying. It facilitates navigation in the virtual environments independently from physical constraints and gravity compared to 2D ground-based locomotion. Unlike walking-based locomotion techniques, 3D flying facilitates high interaction fidelity and reachability of places in the whole 3D space more efficiently. However, these techniques often require elaborate constructions for more immersive experience [31], usage of additional input methods [11], or are specialized to a degree irrelevant for everyday applications [19]. Moreover, they can potentially induce a higher motion sickness compared to teleportation techniques [4, 5, 17]. Therefore, in this work we aim to extend the capabilities of the discrete locomotion techniques. i.e, teleportation, to the 3D to ensure fast and precise locomotion without increasing VR sickness.

2.2 Point & Teleport Locomotion

Teleportation techniques consists of two main operations: (1) aiming at a target and (2) transitioning to a target.

One of the most prominent techniques to aiming at a target remains pointing (or point & teleport), which has recently gained its popularity and become a state-of-the-art in VR games, outperforming gaze-based locomotion techniques [9]. Pointing or aiming at a target is primarily enabled via linear and parabolic casting. It has previously been shown that parabolic casting on the 2D horizontal plane outperforms not only linear casting, but also techniques that use the active play area to steer [24], embodied movements [34], eye tracking [28], and specialized chairs [47] in both speed and precision. Moreover, Valve's developer package [1] already contains a basic implementation for parabolic casting, employing it for a number of popular VR games. However, it is unclear how parabolic and linear casting methods perform in the 3D space.

Regarding the transitioning to a target, *instant* teleportation comes at the price of reduced immersion [34] and a slight reduction in orientation [5, 14]. However, it is easy to use and understand with little effort [14], and most importantly it does not tend to cause VR-specific motion sickness [22]. On the other hand, *continuous* transitioning to a target ensures a better orientation in space and higher feeling of presence [19, 24, 34, 38, 47], but often leads to an increased VR sickness [5, 17]. Therefore, in our work we explore both instant and continuous transitioning to a target in 3D VR space. Moreover, we also investigate an intermediary step between instant and continuous transitioning as an interpolated type of movement, which splits the entire movement length into five equally sized teleportations instead of a single one. However, teleportation in

[1] https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

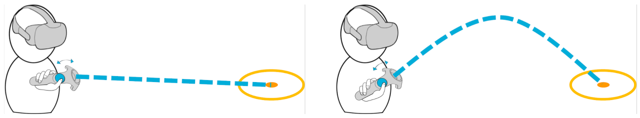

Figure 2: Overview of two aiming methods: linear (left) and parabolic (right).

3D poses challenges, which we describe in the following subsection, followed by the empirical evaluation of six 3D teleportation techniques in terms of speed, precision and VR sickness.

3 TELEPORTATION CHALLENGES IN 3D

Existing teleportation methods in virtual environments primarily focus on the teleportation in 2D space [6, 9, 13, 14, 23]. However, bringing these teleportation methods into 3D space poses two challenges.

The first challenge is related to explicitly setting a teleportation point in 3D space, i.e., a point a user wants to teleport to. The teleportation point in space cannot simply be placed at a hit point with the ground as in 2D. Therefore, it is necessary to set an adjustable maximum distance up to which the parabolic or linear cast is being calculated, and where the teleportation point will be placed. To mitigate this challenge regarding the selection of the teleportation point, we overlaid the touchpad of the controller with a scale in the longitudinal axis, where the pressed point on the axis lies between 0 to 1. In this way, users can choose closer distances by touching at bottom close to 0 and further distances by touching at the top close to 1, without a need for an "active" setting of the distance.

The second challenge is related to the relative placement of the user to the teleportation point. While in 2D the obvious solution is placing the user at ground level, this is more complex in 3D. Users might be placed with their body, hand, head or torso at the 3D teleportation point. To mitigate this challenge, we used the teleportation point as the target position of the controller. However, this way the teleportation would allow the user to fall to a height below ground level, when targeting a point below the user's hand height, and would lead to their feet sinking into the ground. To address this, we compare the real ground level adjusted within the settings of the VR setup with the ground level of the Virtual Environment and cap the latter to the level of the first. With this, we wanted to avoid confusions with the differentiation by conducting the entire experiment mid-air.

4 EVALUATION

In this work, we aim to extend the advantages of 2D teleportation into full three-dimensional space and thus, unlock the vertical movement. This will require a re-assessment of the most common implementation and reevaluation of paradigms for parabolic and linear casts [14], given that target point on ground-level is no longer available. This leads us to the following research question: *"How can we teleport in the 3D space the most efficiently in terms of speed and accuracy without increasing VR sickness?"* To answer this research questions and investigate the efficiency of the proposed 3D teleportation methods in virtual environments, we conducted a controlled lab experiment in the virtual reality space.

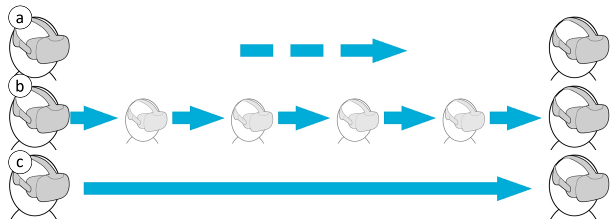

Figure 3: Overview of the types of transition to a target: (a) instant – a user appears at a new location instantaneously, (b) interpolated – a user appears at a new location experiencing four equidistant points between a starting and an ending point and (c) continuous – a user transitions to a new location by continuously moving through space.

4.1 Participants

We recruited 24 participants (identified as 5 female, 19 male) aged between 22 and 33 years old ($M = 26.17, SD = 2.87$). Their previous experience in Virtual Reality spreads equally (8 per group) among the groups of "little to no experience" (<5h), "moderate experience" (5-100h) and "extensive experience" (>100h). Most of the experiences made were with games (12) and other experiments in VR (12). Rarely, they had previously experienced VR demos, e.g., interactive museum exhibitions (4). All participants had normal or corrected-to-normal vision.

4.2 Study Design

The study was designed to be within-subject with four independent variables: (1) aiming method, (2) transitioning to a target, (3) target distance, and (4) target direction. We outline the independent variables in the following.

4.2.1 Aiming Method. As our aim is to inspect the paradigms that have come up over the last years of Virtual Reality development, we are comparing the *linear* and *parabolic* method of aiming a teleportation (Figure 2). To keep both methods comparable, we aimed to limit them to the same maximum distance of 18 meters. While for the linear teleport this constraint implies simply setting this value, for the parabolic teleportation we derived the maximal distance by computing the projectile distance at an angle of 45°of the controller to the ground.

4.2.2 Transitioning to a Target. Within the scope of this paper, we consider three types of transitioning to a target: (1) instant, (2) interpolated, and (3) continuous (Figure 3).

The existing and established method of teleportation is visualised in an *instant* displacement. This method is supported by a visual fade effect to mitigate potential VR sickness in present day Virtual Reality applications. As soon as the teleportation is triggered, the participant's view is faded out over 0.1 s, the actual teleportation takes place and the view fades back in over 0.1 s. We chose this method of *instant* displacement as a baseline.

Alternatively, we investigate a *continuous* linear movement to a target, which leads to a better orientation in space and higher feeling of presence [19, 24, 34, 38, 47]. To reduce the risk of motion sickness for this method, we added comfort bounds at the edge of the user's vision using the Unity asset [2] set to a black fading circle around the outer edges of the vision.

Finally, we propose an *interpolated* type movement with a teleport. On the trajectory leading from the current position to the target position, we calculated four equidistant points, which the user will be teleported to. The user experiences four intermediate stops before arriving at the final destination in a similar manner to the instant teleport. This was meant to be an intermediary step between an instant and continuous movement while allowing for peripheral vision. The combination of two aiming methods and three types of movement led to six 3D teleportation methods in virtual environments.

4.2.3 Target Direction and Distance. The combinations for the other two independent variables of target direction and distance allowed us to create trajectories for collecting coins. Each subsequent coin was randomly spawned in five target directions: (1) left, (2) right, (3) up, (4) down or (5) in front of the preceding one. To incentivize the use of the full possible range of the teleport, we explored different target distances between the coins – 7m, 14m, 21m – with the latter intentionally surpassing the maximum range of a single linear or parabolic teleport. Those distances were chosen as to have a minimum distance which was clearly not manageable without teleportation (twice the available diagonal of the play area) while at the same time being as small as possible to keep the generally occurring relative estimation error [30] to a minimum. This combination of five directions and three distances led to a total of 15 distinct segments. Each distinct segment appeared three times per trial to account for different types of angles in the periphery of vision, which resulted in 45 segments per trial – 15 segments * 3 distances. At the same time, for each trial we excluded the configuration in which a given element was preceded by the same direction or distance. As a segment always consisted of two coins, we had a total of 46 coins in each trail, such that a segment one from coin a to coin b, segment two from coin b to coin c. Collecting the first coin was considered the start time of the trial as previous reorientation was necessary and did not correspond to one of the 15 types of segments. The beginning of the trail was set at a height that would allow each trail generated not to fall below ground level.

4.3 Task

To test six 3D teleportation methods within a fully three-dimensional navigation task, participants had to collect coins in the virtual space as quickly as possible. The virtual environment with coins was designed with minimal distractions. At the beginning of each trial, participants were shown two coins: (1) the one to be collected (active) and (2) the consequent one overlaid with a red cross (inactive) (see Figure 4). The coins were collected by pulling the trigger, when holding the controller not further than one meter away from the active coin's center. The maximum distance was set to avoid accidental triggering. The active coin's center was marked by an inner white ball with a diameter of 10 cm to avoid misestimation to its exact position. A collected coin was accompanied with an audio cue to allow for non-visual feedback and faster orientation towards the next target. When a collected coin disappeared, the inactive

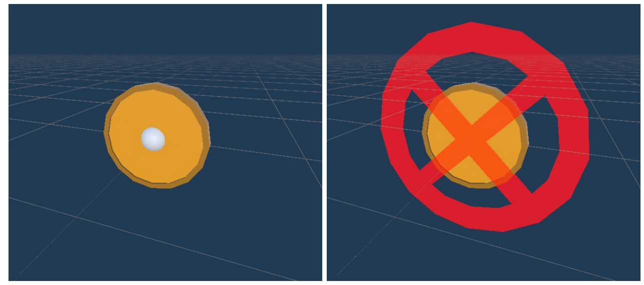

Figure 4: Overview of the two states of targets: an active coin's center is marked by an inner white ball (left) and an inactive coin overlaid with a red cross (right). When an active coin is collected it disappears and an inactive coin loses its overlay and becomes an active one.

coin lost its overlay and the next coin spawned in inactive state. Additionally, we added an arrow pointing in the direction of the next coin for the case participants had difficulties finding it.

4.4 Apparatus

To avoid inconveniences caused by wires, we used a wireless HTC Vive setup for this study, which includes HTC Vive Controller with Deluxe Audio Strap and Wireless Upgrade. The experimental area was calibrated to a size of 2 x 3 x 2.5 (WxLxH) meters with chaperone bounds turned on for participants' safety.

4.5 Measures

To compare the proposed 3D teleportation methods in VR, we measured the following dependent variables:

- *Coin Collection Time (in sec)*: the time necessary to collect each individual coin (starting from the second one). The timer started after a previous coin was collected and stopped when a coin was successfully collected.
- *Coin Collection Offset (in meters)*: for each coin, we measured the distance between controller and centre of the coin after the last teleport before collecting the coin.
- *Number of Teleportations*: for each coin, we counted the number of teleportations necessary to reach a target.
- *Virtual Reality Sickness (VRS):* during each experimental condition participants were asked to assess the level of VRS using a scale from 0 (none) to 20 (extreme) with a time interval of 30 seconds. The question *"How are you feeling right now?"* was played automatically as an audio file and the answers were recorded by the experimenter.
- *Presence*: after each condition every participant assessed the feeling of presence in the virtual environment using the Igroup Presence Questionnaire (IPQ). The scores were calculated based on the official source for the IPQ questionnaire [3].
- *Ease and frequency of use, intuitivity, orientation, speed and fatigue*: after each condition participants were asked to asses ease and frequency of use, intuitivity, orientation, speed and fatigue of the method using a 5-point Likert scale (1 – the lowest score, 5 – the highest score).

[2] https://assetstore.unity.com/packages/tools/camera/vr-tunnelling-pro-106782

[3] http://www.igroup.org/pq/ipq/data.php

	CCT, s		Coin offset, m		# of Teleportations		VRS Range	IPQ			
	M	SD	M	SD	M	SD		GP	SP	INV	ER
Linear-Instant	3.76	1.41	0.62	0.28	1.79	0.68	[0;3]	5	3.2	3	1.75
Linear-Interpolated	4.17	1.44	0.85	0.34	1.68	0.58	[0;3]	5	3.3	3.5	1.75
Linear-Continuous	4.11	1.68	0.84	0.45	1.68	0.62	[1;4]	5	3.2	3.375	1.875
Parabolic-Instant	4.54	2.45	0.59	0.24	1.95	0.76	[1;3]	5	3.2	3.25	2
Parabolic-Interpolated	4.79	2.30	0.90	0.39	1.88	0.82	[1;3]	5	3	3.125	1.75
Parabolic-Continuous	4.59	2.13	0.84	0.43	1.85	0.74	[0;3]	5	3.2	3	1.75

Table 1: Summary of results per method of teleportation: the table shows mean and standard deviation values for Coin Collection Time (CCT), Coin offset, and number of teleportations required to collect a coin. VRS refers to the range of VR sickness score and Igroup Presence Questionnaire score (IPQ) shows medians per subscale.

4.6 Procedure

For this study, we adhered to our universities health department's guidelines for user studies during the COVID-19 pandemic. All testing equipment was disinfected and the hall used was aired out for a minimum of one hour between participants. After obtaining informed consent, we collected participants' demographic data. Afterwards we provided a brief overview of the procedures, which included explanations of teleportation methods and the task. We started the experiment, when participants felt comfortable. Before the start of each condition participants were given a chance to familiarize themselves with the teleportation method. When they felt comfortable with it, participants were transported to the beginning of the trail, where the coins started to spawn. During each trial the audio output was set to speakers next to the play area to allow the investigator to communicate with the participants. At the end of each trial, participants heard an audio cue as an indication to take off the headset and fill out a questionnaire regarding the teleportation method. At the end of the study, we interviewed the participants about their preferences for the different teleportation methods. The entire study lasted approximately 75 minutes.

5 RESULTS

We found that linear target aiming combined with instant transitioning has the highest performance in the mid-air environment in terms of speed and accuracy. Given the non-parametric nature of the collected data, we applied the aligned rank transform for non-parametric factorial analyses [43]. For pairwise comparisons we used a Bonferroni correction. The overview of the results are shown in Table 1. We outline all results in details in the following subsections.

5.1 Coin Collection Time

We discovered that participants were faster collecting coins using a linear ($M = 4.01\ sec, SD = 1.53$) than parabolic ($M = 4.64\ sec, SD = 2.3$) using a non-parametric factorial analyses [43]. As for the type of transitioning, instant ($M = 4.15\ sec, SD = 2.03$) was shown to be the fastest, followed by continuous ($M = 4.35\ sec, SD = 1.93$) and interpolated ($M = 4.48\ sec, SD = 1.94$) types. Both of these findings were supported by the statistically significant main effects for the aiming method ($F(1, 2047) = 87.5, p < 0.001$) and the type of transitioning ($F(2, 2047) = 28.4, p < 0.001$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.001$) for both independent variables (Figure 5 left).

As for the target direction, we discovered that the teleportation forward takes the shortest amount of time ($M = 3.74\ sec, SD = 1.48$), followed by upwards ($M = 3.96\ sec, SD = 1.79$), left ($M = 4.32\ sec, SD = 1.85$), right ($M = 4.37\ sec, SD = 2.15$) and downwards ($M = 5.25\ sec, SD = 2.19$). This finding was confirmed by a statistically significant main effect for target directions ($F(4, 2047) = 109.9, p < 0.001$) and statistically significant differences between all pairs of directions ($p < 0.001$), except for left and right ($p > 0.05$) (Figure 6 left).

As for the target distance, our statistical analysis revealed that the closer the target is, the shorter is the coin collection time. It takes the shortest amount of time to teleport to the targets located at 7 meters ($M = 3.34\ sec, SD = 1.57$) distance, followed by 14 ($M = 4.33\ sec, SD = 1.64$) and 21 ($M = 5.31\ sec, SD = 2.15$) meters. This finding is confirmed by a statistically significant main effect for the target distance ($F(2, 2047) = 606.2, p < 0.001$). The post-hoc analysis has shown that all pairs have statistically significant differences ($p < 0.001$) (Figure 6 left).

Finally, our statistical analysis revealed three statistically significant interaction effects for aiming method*target direction ($F(4, 2047) = 11.42, p < 0.001$), aiming method*target distance ($F(2, 2047) = 9.24, p < 0.001$) and target direction*target distance ($F(8, 2047) = 3.14, p < 0.01$). As for the first interaction effect, the post-hoc analysis has shown that teleportation in direction downwards, forward and left with linear aiming method is significantly faster than with parabolic ($p < 0.01$), but not for directions right and upwards ($p > 0.05$). As for the second interaction effect, we have discovered that teleportation at 7, 14 and 21 meters is faster with the linear than with the parabolic aiming method ($p < 0.001$). As for the third interaction effect, we found that teleportation downwards takes longer than in any other direction ($p < 0.001$) for all three target distances (7, 14 and 21 meters). Moreover, teleportation left and right takes longer than going forward for all target distances: 7 ($p < 0.001$), 14 ($p < 0.05$), and 21 ($p < 0.01$) meters. Finally, for the targets located at 7 meters distance it takes longer to teleport left or right than upwards ($p < 0.001$).

5.2 Coin Collection Offset

We discovered that participants achieve the shortest coin offset using the instant ($M = 0.6\ m, SD = 0.26$) type of transitioning compared to continuous ($M = 0.84\ m, SD = 0.44$) or interpolated

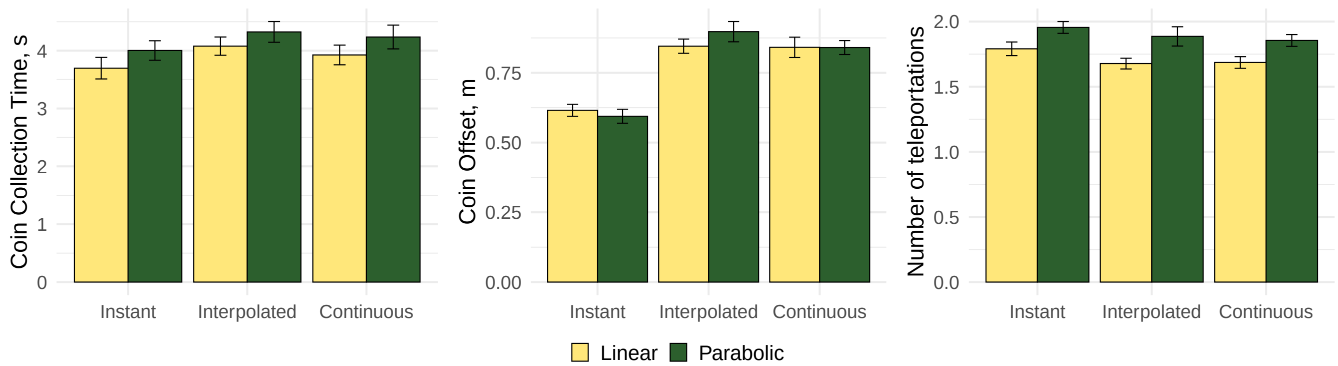

Figure 5: Overview of results averaged over teleportation methods: means and standard errors for coin collection time (left), coin collection offset (center) and number of teleportations (right).

($M = 0.87$ $m, SD = 0.37$) methods. This finding was supported by a statistically significant main effect for the type of transitioning ($F(2, 2047) = 195.4, p < 0.001$). The post-hoc analysis has shown that all pairwise comparisons were statistically significantly different: instant-interpolated ($p < 0.001$), instant-continuous ($p < 0.001$), and continuous-interpolated ($p < 0.01$). However, the coin collection offsets for linear ($M = 0.77$ $m, SD = 0.38$) and parabolic ($M = 0.77$ $m, SD = 0.39$) aiming methods were comparable, since we did not observe a statistically significant main effect ($F(1, 2047) = 0.3, p > 0.05$) (Figure 5 middle).

As for the target direction, we found that teleportation downwards ($M = 0.73$ $m, SD = 0.41$) and forward ($M = 0.74$ $m, SD = 0.26$) had the shortest coin collection offset, followed by left ($M = 0.79$ $m, SD = 0.33$), right ($M = 0.8$ $m, SD = 0.4$), and upwards ($M = 0.81$ $m, SD = 0.48$). This finding is supported by a statistically significant main effect ($F(4, 2047) = 6.45, p < 0.001$). The pairwise analysis has shown that only teleportation downwards had significantly shorter coin collection offsets compared to direction left ($p < 0.001$), right ($p < 0.001$), and upwards ($p < 0.01$). The remaining pairwise comparisons were not statistically significant ($p > 0.05$) (Figure 6 middle).

As for the target distance, our analysis revealed that the coin offset for targets located at 7 meters distance ($M = 0.83$ $m, SD = 0.48$) is larger compared to 14 ($M = 0.74$ $m, SD = 0.31$) and 21 ($M = 0.75$ $m, SD = 0.33$) meters. This finding is supported by a statistically significant main effect ($F(2, 2047) = 7.71, p < 0.001$). The pairwise comparisons have shown that the coin offset is significantly larger for the 7 meters distances compared to 14 ($p < 0.01$) and 21 ($p < 0.01$). However, there was no statistically significant difference between 14 and 21 meters ($p > 0.05$) (Figure 6 middle).

Lastly, our statistical analysis has revealed one statistically significant interaction effect for the type of transitioning*target direction ($F(8, 2047) = 2.42, p < 0.05$). The pairwise comparisons have shown that the instant type of transitioning leads to lower coin collection offsets in all directions compared to continuous ($p < 0.001$) and interpolated ($p < 0.001$). However, the coin collection offsets are comparable for the continuous and interpolated types of transitioning in all directions ($p > 0.05$).

5.3 Number of Teleportations

We discovered that participants require a smaller number of teleportations to reach a target using the linear ($M = 1.71, SD = 0.63$) than the parabolic ($M = 1.89, SD = 0.77$) aiming method. This finding is supported by a statistically significant main effect ($F(1, 2047) = 130.1, p < 0.001$). Additionally, we found that the continuous type of transitioning requires the lowest number of teleportations ($M = 1.77, SD = 0.69$), followed by interpolated ($M = 1.78, SD = 0.72$) and instant ($M = 1.87, SD = 0.72$). This finding is supported by a statistically significant main effect ($F(2, 2047) = 23.2, p < 0.001$). The post-hoc analysis has shown that the instant type of transitioning requires a higher number of teleportations compared to the continuous ($p < 0.001$) and interpolated ($p < 0.001$) types of transitioning. However, the interpolated and continuous types of transitioning lead to a comparable number of teleportations ($p > 0.05$) (Figure 5 right).

Regarding the target direction, the number of teleportations was found to be highest downward ($M = 2.01, SD = 0.82$), followed by upward ($M = 1.79, SD = 0.71$), leftward ($M = 1.74, SD = 0.66$), rightward ($M = 1.76, SD = 0.68$), and forward ($M = 1.73, SD = 0.63$). This result is supported by a statistically significant main effect ($F(4, 2047) = 58.1, p < 0.001$). Pairwise analysis showed that only downward teleportation had a significantly higher number of teleportations compared with the left ($p < 0.001$), right ($p < 0.001$), upward ($p < 0.001$), and forward ($p < 0.001$) directions. The remaining pairwise comparisons were not statistically significant ($p > 0.05$) (Figure 6 right).

Regarding target distance, we found that participants required a higher number of teleportations to the more distant targets: 7 ($M = 1.18, SD = 0.34$), 14 ($M = 1.76, SD = 0.48$), and 21 meters ($M = 2.48, SD = 0.56$). This result is supported by a statistically significant main effect for target distance ($F(2, 2047) = 2506.7, p < 0.001$). Post-hoc analysis showed that a smaller number of teleportations are required to reach targets at a distance of 7 meters compared to 14 ($p < 0.001$) and 21 ($p < 0.001$), and that 14 meters requires more teleportations than 21 ($p < 0.001$) (Figure 6 right).

Finally, statistical analysis revealed five statistically significant interaction effects for: (1) aiming method * target direction ($F(4, 2047) = 35.5, p < 0.001$), (2) type of transitioning * target direction

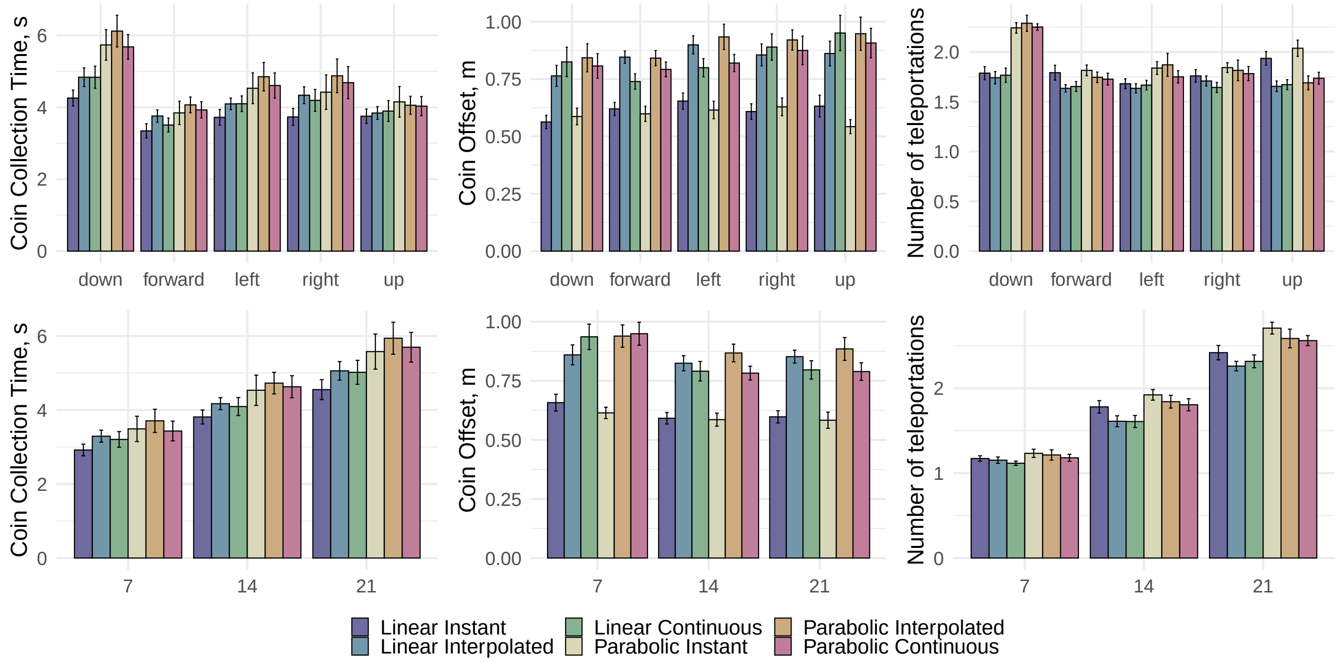

Figure 6: Overview of results per teleportation direction (downwards, forward, left, right, upwards) in the upper row and distance to targets (7, 14, 21 meters) in the lower row: means and standard errors for coin collection time (left), coin offset (center) and number of teleportations (right).

($F(8, 2047) = 5.4, p < 0.001$), (3) aiming method * target distance ($F(2, 2047) = 28.3, p < 0.001$), (4) type of transitioning * target distance ($F(4, 2047) = 3.9, p < 0.01$), (5) target direction * target distance ($F(8, 2047) = 13.6, p < 0.001$). Regarding the first interaction effect, we found that participants required a smaller number of teleportations in the linear method than in the parabolic one in the downward ($p < 0.001$) and leftward ($p < 0.01$) directions. However, in the other directions, the number of teleportations is comparable ($p > 0.05$). As for the second interaction effect, we found that both the continuous and interpolated types of transitioning require a smaller number of teleportations than the instant one in the upward direction ($p < 0.001$). The difference between the continuous and interpolated types of transitioning in the upward direction is not statistically significant ($p > 0.05$). The differences for other directions between the remaining pairs are not statistically significant ($p > 0.05$). As for the third interaction effect, we found that the linear aiming method leads to a lower number of teleportations than the parabolic one for all distances to the targets: 7 ($p < 0.05$), 14 ($p < 0.001$), and 21 meters distance ($p < 0.001$). Regarding the fourth interaction effect, we found that the instantaneous type of transitioning required a higher number of teleportations than the continuous ($p < 0.001$) and interpolated ($p < 0.001$) ones for the targets located at a distance of 14 meters. In addition, the interpolated type of transitioning was found to require a smaller number of teleportations than the instant one ($p < 0.01$) for the targets located at a distance of 21 meters. The differences between the other pairwise comparisons were not statistically significant ($p > 0.05$). Finally, as with the fifth interaction effect, the number of teleportations in the downward direction was found to be higher for the targets located at 14 and 21 meters than in all other directions ($p < 0.001$). The differences between the other pairwise comparisons were not statistically significant ($p > 0.05$).

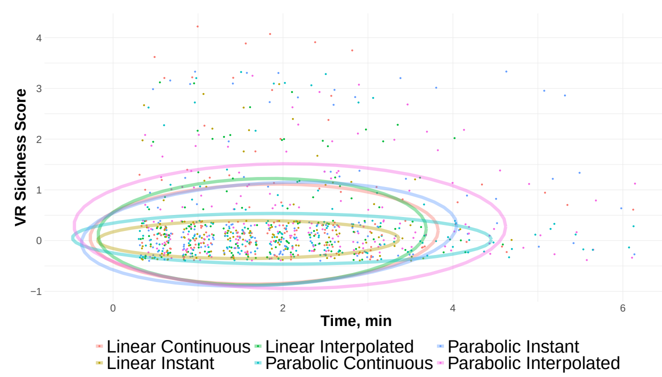

Figure 7: Overview of VR sickness trends over time per condition using 90% data ellipses. Data ellipses construct and provide a set of x and y coordinates for each probability value, and 90% ellipses contain the underlying mean. Longer ellipses indicate constant VR sickness over time, higher ellipses indicate an increase in VR sickness, and tilted ellipses indicate an increase in VR sickness over time. Given a high number of data points with the same scores, they are placed next to each other.

	Ease of Use		**Intuitivity**		**Orientation**		**Frequency of Use**		**Speed of Finding**		**Fatigue**	
Teleport.	Md	IQR	Md	IQR	Md	IQR	Md	IQR	Md	IQR	Md	IQR
Lin. Inst.	5	0.25	5	0	4	1	4	1	5	1	1	1
Lin. Inter.	4.5	1	5	1	4	1.5	4	1.25	4	1	1	1
Lin. Cont.	5	1	5	0.25	4	1.25	4.5	1	4	1.	1	1
Par. Inst.	4	2	4	1.25	3.5	2.25	4	1.5	4	1.25	1	1
Par. Inter.	4	2	4	1.25	4	1.25	3	2	4	0.25	1	1
Par. Cont.	4	2	4	1.25	4	1.5	4	1.25	4	1	1	1

Table 2: Results of the subjective feedback using 5 -point Likert scales. Md = median, IQR = interquartile range, Lin. = Linear, Par. = Parabolic, Inst. = Instant, Inter. = Interpolated, Cont. = Continuous.

5.4 Virtual Reality Sickness and Presence

Although the maximum values for the VR sickness were around 4, we observed a tendency for a higher spread of points for the parabolic interpolated method compared to linear instant and parabolic continuous using 90% data ellipses (Figure 7). Moreover, the development over time indicates a decrease of VR sickness using linear instant teleportation.

We calculated the IPQ scores for the general presence and its subscales, which are shown in Table 1. Our analysis has shown that our teleportation methods induced a comparable level of presence in the virtual environments, given no statistically significant differences for the general presence and all subscales.

5.5 Subjective Feedback: Ease and Frequency of Use, Speed, Orientation

In the following, we outline the statistical analysis of subjective feedback based on the Likert scale. The summary of the descriptive statistics is shown in Table 2 and Figure 8.

We found that the linear aiming method was perceived to be easier ($F(1, 115) = 11.9, p < 0.001$) and more intuitive ($F(1, 115) = 15.3, p < 0.001$) to use based on the subjective feedback. Both findings are supported by a statistically significant main effects for aiming method with regards to the ease of use ($t(115) = 3.5, p < 0.001$) and intuitiveness ($t(115) = 3.91, p < 0.001$). We did not find a statistically significant main effect for the type of transitioning and interaction for both factors.

Regarding the subjectively perceived speed of finding and selecting a coin, we found that the linear targeting method was subjectively faster than the parabolic one. This finding is supported by a statistically significant main effect for the aiming method ($t(115) = 4.003, p < 0.001$). No further main or interaction effects were observed for this variable. Participants have further expressed their preference for using linear aiming method more frequently compared to the parabolic one. This effect was observed via a statistically significant main effect for the aiming method ($t(115) = 4.77, p < 0.001$). Furthermore, we did not observe statistically significant main or interaction effects for orientation and fatigue.

5.6 Problems and Preferences

We discovered that the majority of the participants expressed a general preference for teleportation in 3D with a linear aiming method (N = 21). As for the type of transitioning, ten participants ranked instant movement as the preferred one, followed by continuous (N = 8) and interpolated (N = 6). Regarding the teleportation methods, linear instant teleportation was preferred based on the participants' ranking (N = 9), followed by linear continuous (N = 7) and linear interpolated (N = 5). The aforementioned preferences for the linear instant teleportation were justified by the ease of use and orientation in space. As some of participants mentioned: *"I liked linear much better than parabolic, I felt that linear offered only advantages."* [P6, M, 26 years old], *"Parabolic makes more sense on the ground. In free space, without any obstacles, it's easier for me to directly aim a target rather than approximating it with the controller."* [P16, M, 33 years old], or *"going up was more straightforward with this method [linear]"* [P3, F, 24 years old].

As for the other types of preferences, ten participants found linear instant teleportation as the one that lead to the lowest level of VR sickness, linear continuous as the best for orientation in space (N = 12), linear instant as the most precise (N = 13) and the fastest (N = 14). These findings were supported by the following statements from the participants: *"Instant – for reaching single targets efficiently. Continuous – to reach them on-the-go while sliding through them."*[P19, M, 30 years old], *"Instant feels quicker, more precise, less tedious"* [P1, M, 27 years old], and *"With continuous method, it was easiest to keep track of my position / movement relative to the world this way"* [P4, M, 26 years old].

6 DISCUSSION AND FUTURE WORK

In general, we discovered that teleportation using a linear target aiming method outperforms the parabolic one in a mid-air environment in terms of speed and accuracy. Moreover, instant transitioning to the target was the fastest and the most accurate. Therefore, linear target aiming combined with instant transitioning is shown to be the most efficient teleportation method in 3D without causing VR sickness. We discuss these results and their implications in the following subsections.

6.1 Linear, Parabolic or Both?

Our results suggest that linear target aiming is better suited for 3D teleportation in VR compared to 2D. Although the collection coin offset was comparable for both aiming methods, participants were faster and needed a lower number of teleportations using linear target aiming. This can be explained by the fact that linear aiming facilitates a clearer understanding at which point in 3D space participants are going to end up after teleportation compared

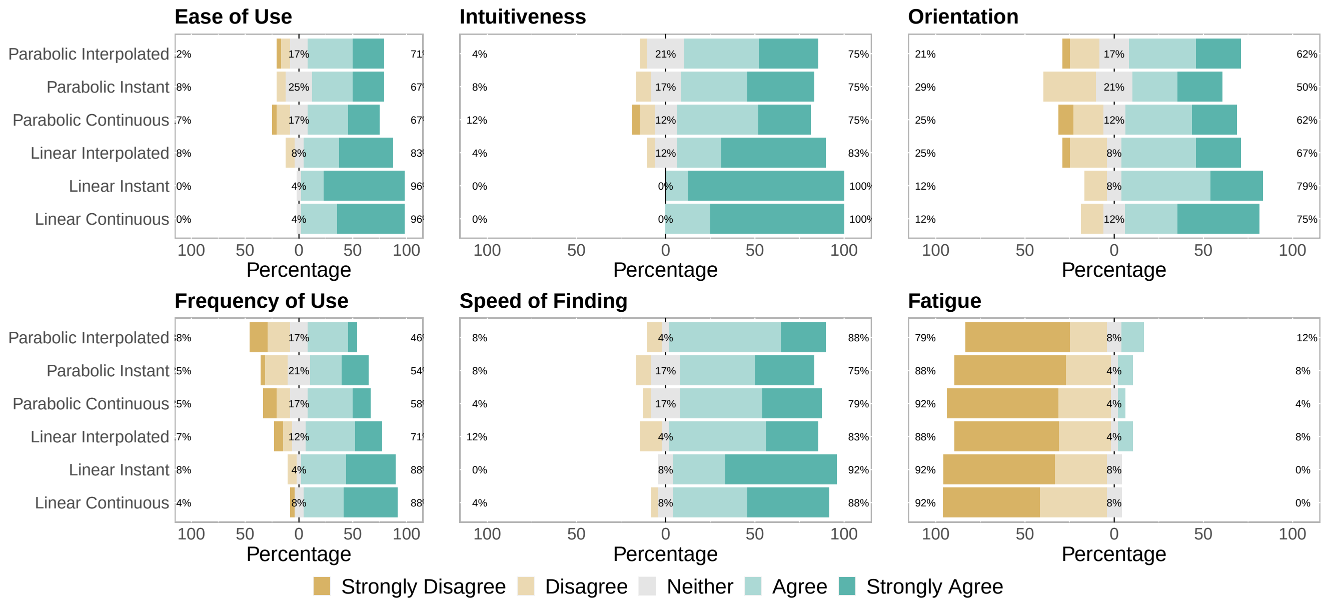

Figure 8: Overview of Likert data for each question: ease of use, intuitiveness of methods, assistance by orientation in space, preference for using the methods frequently, subjective assessment of speed when finding a target and fatigue.

to parabolic, which requires a longer time to adjust the targeting and more teleportations to reach it. 2D teleportation, however, was shown to be the most efficient with parabolic casting and became a standard method over the last couple of years [9, 14, 39]. Therefore, the question we ask ourselves is: *"Which teleportation method is the most efficient in hybrid environments?"* By hybrid environments we refer to spaces, where teleportation on the ground and mid-air are possible, unlike the setup in our study where teleportation was focused on mid-air only. We assume that in hybrid spaces a combination of linear and parabolic casting might be beneficial, given their advantages for different circumstances. Gravitational acceleration is the only parameter that differentiates the linear ($F = 0m/s^2$) and parabolic casts ($F = -9.81m/s^2$). There are different possible ways to combine them. For example, a user can use a toggle button on the controller to switch between linear and parabolic method on demand, or it can be based on the user preferences adjusted to the type of the virtual 3D space: if the space is primarily empty and does not have many 2D surfaces to teleport to, the user's default option would be linear aiming method, and vice versa. Alternatively, switching can be controlled by the angle at which the user holds the controller relative to the ground, e.g., the parabolic cast could be activated when the controller is held at an angle of -45° to +45°. Casting outside of this range would enable a linear cast in 3D space. How both targeting techniques can be combined for exploration of hybrid spaces is an interesting point to explore in future work.

6.2 Fly Me to the Moon... Instantly

Discrete (or instant) locomotion in 3D outperformed continuous and interpolated types of transitioning in terms of speed and accuracy. Participants were quickly localized at the new location and after a short reorientation in space could aim for another target. However, it is important to note that the low coin collection offset for the instant transitioning to the target happens at the cost of a higher number of teleportations, which allows participants to readjust their targeting and come closer to the target. In contrast, the advantage of continuous and interpolated transitioning methods allowed participants to collect coins mid-movement, i.e., collect multiple coins in one teleportation. This could have had a positive effect on the coin collection speed, but we did account for these situations in our data analysis to ensure a fair comparison towards instant transitioning. However, it might be necessary to conduct a similar experiment in the future with a focus only on the accuracy. Although our results have shown that instant teleportation is the fastest method for transitioning to the next target, it does not account for the transition time compared to the other two methods. However, the transition time is not lost per se using continuous transitioning, since participants had a chance to orient themselves in relation to the consequent target before teleporting. This difference in the nature of transitioning cannot be ruled out and future studies regarding the effects of transition are necessary.

6.3 How far can we go and in which direction?

Distant targets reduce the speed and accuracy of teleportation in 3D. As our results have shown, the further the object is from the user, the longer it takes to reach it. The same is true for the number of attempts and the size of the offset, which become comparable at distances of 14 meters or more. This is a rather obvious and logical result, as it allows for distance estimation, which is necessary for target placement, e.g., to create different difficulty levels in VR games. Moreover, the results regarding the difficulty with downward direction were also confirmed for further distances (14 and 21 meters) and showed reduced precision in target selection.

We found that the downward direction plays a special role in 3D teleportation. Our results have shown that reaching a target located in the downward direction requires a longer amount of time and a higher number of teleportations compared to all other directions. This implies that participants spent more time trying going downwards than upwards as an opposite direction. A possible reason for this difference can be explained by the fact that looking down leads to slight slipping of the HMD, which might reduce participants' ability to properly estimate distances. In contrast, we found that teleportation up and down leads to lower coin offsets compared to left, right and forward. This can be explained by the fact that participants needed to teleport more often in these directions, which led to executing the last teleport closer to the target, i.e., shorter coin collection offset.

7 LIMITATIONS

When evaluating the proposed 3D teleportation methods, we encountered some limitations. The arrow placed under participants was intended to play a role of an orientation aid in case of difficulties finding the next target. However, some participants relied on it as the primary orientation mechanism, which in turn may have affected the influence of peripheral vision and the effect of transition to the next target. Future studies will therefore need to consider the adequacy of orienting cues in such situations. In addition, the task used in the experiment focused on target acquisition, which involved teleporting to a target as quickly as possible. Focusing on more accurate target acquisition may have altered the results. In addition, we did not use game mechanics to influence the use of teleportation methods and put pressure on users to see how this would affect their performance in more stressful situations. We acknowledge that the performance of the teleportation methods could affect the results in different game situations. The 3D space presented in the experiment was free of obstacles and participants were free to teleport in any direction. Therefore, our results may not be directly applicable to 3D virtual environments with obstacles, which requires further investigation in future studies. Our evaluation included primarily male participants between the ages of 22 and 33 and covered a limited number of subjective measures related to VR teleportation, such as enjoyment and level of engagement, but it offers many insights related to ease and frequency of use, intuitiveness, orientation, and fatigue.

8 CONCLUSION

In this paper, we propose six teleportation methods in virtual environments based on the combination of two existing aiming methods (linear and parabolic) and three types of transition to a target (instant, interpolated and continuous). To investigate the performance of the proposed teleportation methods, we conducted a controlled lab experiment with a mid-air coin collection task to assess speed, accuracy and VR sickness. We discovered that the combination of linear aiming method and instant transitioning leads to faster and more precise target selection without inducing a high level of VR sickness. Additionally, we found that teleportation downwards is more challenging and requires a higher number of teleportations to reach the target compared to other directions, but it leads to smaller target offsets. Lastly, our results have shown that the linear aiming method leads to a lower number of teleportations than parabolic for all tested (7, 14, 21, meters) distances to the targets.

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