UndoPort: Exploring the Influence of Undo-Actions for Locomotion in Virtual Reality on the Efficiency, Spatial Understanding and User Experience

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Figure 1: We present UndoPort, an extension of the point&teleport locomotion technique with undo actions. UndoPort allows users to revert changes to their position and orientation and, thus, allows users to jump back to previously visited waypoints. In this work, we evaluate undo actions in terms of their impact on efficiency, local understanding, and user experience.

ABSTRACT

When we get lost in Virtual Reality (VR) or want to return to a previous location, we use the same methods of locomotion for the way back as for the way forward. This is time-consuming and requires additional physical orientation changes, increasing the risk of getting tangled in the headsets' cables. In this paper, we propose the use of undo actions to revert locomotion steps in VR. We explore eight different variations of undo actions as extensions of point&teleport, based on the possibility to undo position and orientation changes together with two different visualizations of the undo step (discrete and continuous). We contribute the results of a controlled experiment with 24 participants investigating the efficiency and orientation of the undo techniques in a radial maze task. We found that the combination of position and orientation undo together with a discrete visualization resulted in the highest efficiency without increasing orientation errors.

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CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Virtual reality**; Pointing.

KEYWORDS

Virtual Reality, Locomotion, Teleport, Undo

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1 INTRODUCTION

When exploring unfamiliar territory or collecting items in our known surroundings, we are often faced with the need to retrace paths to get to previous waypoints, such as junctions or a central starting point. Similar to the real world, this backtracking of known routes with the goal of reaching a previously visited waypoint is particularly common in Virtual Reality (VR), where exploration tasks such as finding [26] or collecting [62] items or information are essential mechanics in gaming [8] and learning environments [41, 50, 57]. In familiar environments, this repetitive traversal of known locations reduces exploration efficiency. In unfamiliar environments, difficulty relocating places recently visited [18] can additionally lead to disorientation, lower performance, and spatial knowledge acquisition [19].

While this *going back* is a necessity to reach previously visited locations in reality, locomotion in VR is not subject to the physical laws of reality. From point&click teleport [10] or walk-in-place techniques [60] to foot movements [32, 65] or weight shifting in chairs [63], research and industry have proposed a plethora of artificial locomotion techniques to address the mismatch between the limited size of the physical tracking space and the potentially boundless vastness of virtual worlds. While practical and valuable for exploring VR environments, we still employ the same method of locomotion to return to a previous waypoint, just as we would in reality.

In this paper, we go beyond state-of-the-art and add to the body of research in VR locomotion techniques by exploring undo-actions for locomotion in VR to quickly return to previous waypoints. For this, we propose to record the user's locomotion history and allow them to jump back to any previous waypoint by pressing a button (see fig. 1). We explore the proposed undo concept as an extension of point-and-click teleport, which we chose as a baseline due to its status as the de-facto standard for locomotion in VR in industry, as well as the inherent existence of waypoints.

The contribution of this paper is two-fold. First, we contribute the results of a controlled experiment assessing the influence of undo actions on efficiency, spatial understanding, and user experience in a VR maze task. Here, we investigated eight different implementations of such an undo concept based on the possibility of undoing 1) position and 2) orientation changes together with 3) two different visualizations of the undo step (discrete and continuous). Second, based on the results of the controlled experiment, we contribute a set of guidelines and lessons learned for the future usage of undo actions to support locomotion in VR.

2 RELATED WORK

A large body of prior work on 1) locomotion techniques for virtual reality heavily influenced our work. In the following section, we discuss these works with an in-depth focus on 2) point&click locomotion techniques.

2.1 Locomotion in Virtual Reality

While virtual worlds are only constrained in their spatial dimensions by the designer's imagination, the tracking space in the physical world is not. This mismatch limits the suitability of natural human motion as a means of locomotion in VR to room-scale-based virtual environments [38]. As a solution to this mismatch between the limited size of the tracking area and the potentially unlimited virtual worlds, research has proposed a wide variety of artificial locomotion methods that decouple movement in the physical (tracked) world from movement in the virtual world. Locomotion Vault[1] [20] provides a comprehensive overview of locomotion techniques. Many different classifications and categorizations exist for such artificial locomotion techniques for VR in the literature. However, a central criterion of distinction is typically the classification into 1) continuous or 2) discrete locomotion techniques [6, 70].

Continuous locomotion techniques visually resemble the way we are experiencing locomotion in the physical world by applying changes in translation in the virtual scene over time [9], completely decoupling virtual locomotion from the translation of the user's body in the physical world. Such techniques leverage controllers [23] or other accessories like chairs [28, 44, 53, 63] or shoes [40]. Further, research also proposed to leverage head [61] or hand gestures [12, 24, 55]. As another possible solution, techniques like treadmills [11], in-place [36, 39], scaled [2, 66] or redirected walking [45] alter the user's visual perception to allow for unconstrained continuous movement in the virtual world while walking on-spot or in small circles in the physical world. In recent years, research has expanded such continuous locomotion techniques from 2D to 3D [14, 52, 54, 71] environments. While practical and valuable, continuous locomotion techniques are known to be prone to cybersickness [43] or require larger tracking areas [23].

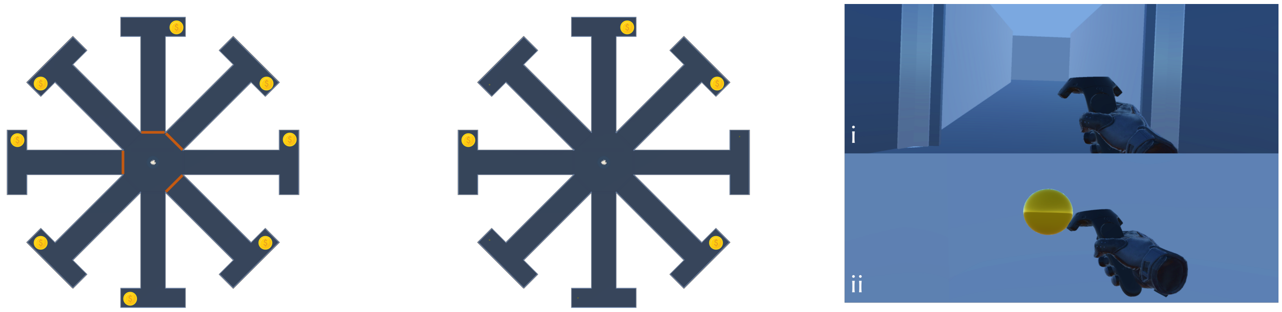
Research proposed discretizing the target selection and locomotion process to overcome these limitations of continuous locomotion techniques. As the most prominent example, teleportation techniques such as point&teleport [10, 26], portals [25], or fixed nodes [29] allow users to skip the movement but directly jump to (intermediate) target locations. Research has shown that such discrete locomotion techniques allow for fast [43] and accurate [26] travel while lowering the problem of cybersickness [29]. However, research showed that the visual jumps could break the users' sense of presence [43] and decrease spatial awareness [9], diminishing their usefulness in certain situations.

Considering the discussed advantages and disadvantages of continuous and discrete locomotion techniques, we opted to build our proposed technique on top of point&teleport, the most prominent discrete locomotion technique. In the following section, we present a more in-depth discussion of point&teleport. For a more detailed classification of general VR locomotion techniques, we refer to the excellent works of Boletsis [6] and Zayer et al. [70].

2.2 Point&Click Teleport

As the most prominent example of a discrete locomotion technique, point&teleport has gained substantial interest from the research community and has become the de-facto standard in commercial VR games. While Bowman et al. [9] already explored pointing-based locomotion techniques in 1997 and others further explored the topic [7, 25], Bozgeyikli et al. [10] first introduced the name and compared point&teleport to walk-in-place and joystick-based locomotion.

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



(a) Radial Maze Task (Training Phase) **(b) Radial Maze Task (Experiment Phase)** **(c) Study Environment**

Figure 2: The radial maze task used in the controlled experiment. During the (a) training phase, the participants' task was to collect the coins from the initially open four coridors. After participants had collected the last coin, the remaining four coridors opened for the (b) experimental phase. Again, the participants' task was to collect the remaining four coins by (c) teleporting through the maze and pressing a button close to the coins.

In recent years, research proposed a variety of extensions and modifications to point&teleport. Funk et al. [26] and Bozgeyikli et al. [10] explored adjusting the users' orientation during the aiming phase. Further, research explored other body parts, such as eye [37] or head gaze [15] and foot movements [13, 65] to select the target. Finally, Matviienko et al. [42] extended point&teleport to 3D locomotion by enabling users to cut off the ray and Weissker et al. [64] and Rasch et al. [51] extended point&teleport for joint multi-user locomotion.

Further, research proposed various solutions to overcome users' spatial understanding and orientation problems. Cmentowski et al. [16] and Griffin and Folmer [27] explored a third-person view for point&teleport. Further, Xu et al. [68] compared point&teleport to joystick and walk-in-place locomotion and did not find significant differences regarding the spatial understanding of users. As a promising solution, Bhandari et al. [5] proposed quickly and continuously moving the user to the target location instead of fading the users' view in and out.

While practical and valuable, today's point&teleport techniques require us to physically turn around and use the same locomotion technique to return to previously visited waypoints. This process is time-consuming and can lead to tangling in cables [26]. As a possible solution, we explore undo-actions to allow users to return to previous waypoints without the need to rotate physically. To the best of our knowledge, there exists no prior literature explicitly focusing on returning to previously visited waypoints to backtrack the last steps of the locomotion. Following the promising results of Bhandari et al. [5], we further included the use of undo-actions for both types of motion visualization.

3 METHODOLOGY

We conducted a controlled experiment to investigate the accuracy, efficiency, and user experience of undo-actions for locomotion actions as an addition to point&click teleport as today's de-facto standard VR locomotion technique. More specifically, we investigated the following research questions:

RQ1 How does the ability to reset the position change of a locomotion action influence the accuracy, efficiency, and user experience of locomotion in VR?

RQ2 How does the ability to reset the orientation change of a locomotion action influence the accuracy, efficiency, and user experience of locomotion in VR?

RQ3 How does the ability to reset both the change in position and orientation of a locomotion action influence the accuracy, efficiency, and user experience of locomotion in VR?

3.1 Design and Task

We designed a controlled experiment in which participants used varying combinations of position- and orientation-undo for locomotion in a VR maze task. To explore users' performance in terms of efficiency while also accounting for potential negative influences of the proposed techniques on participants' spatial understanding and memory, we used an adapted 8-arm radial maze task.

3.1.1 Radial Arm Task. The radial arm maze task was first used to assess the spatial abilities of rodents by Olton and Samuelson [48] in 1976. Since then, the task has been adapted for use with humans in real [46, 47, 59] and virtual [4, 34] settings. The basic version of the task consists of a central room, from which a certain number (usually 8) uniform corridors spread. At the end of the corridors, there are hidden rewards that the test subject is supposed to reach. There are a variety of variations of the radial arm task in the literature, which vary in the exact task, the number of arms, and the amount of external information through visual cues in the world. Further, the literature distinguishes radial maze tasks between free-choice and forced-choice variants, depending on whether all arms are open at the beginning (free-choice) or whether a specific subset of the arms must be visited first (forced-choice) [49].

To exclude the influence of external visual cues and prevent the strategic circular progression, we adapted an uncued forced-choice radial maze task as follows: From the central room, 8 uniform corridors depart, each, in turn, branching at the end in a T-junction. The central room is connected to each corridor through a door (see fig. 2a). A coin is hidden in one of the two T corridors for

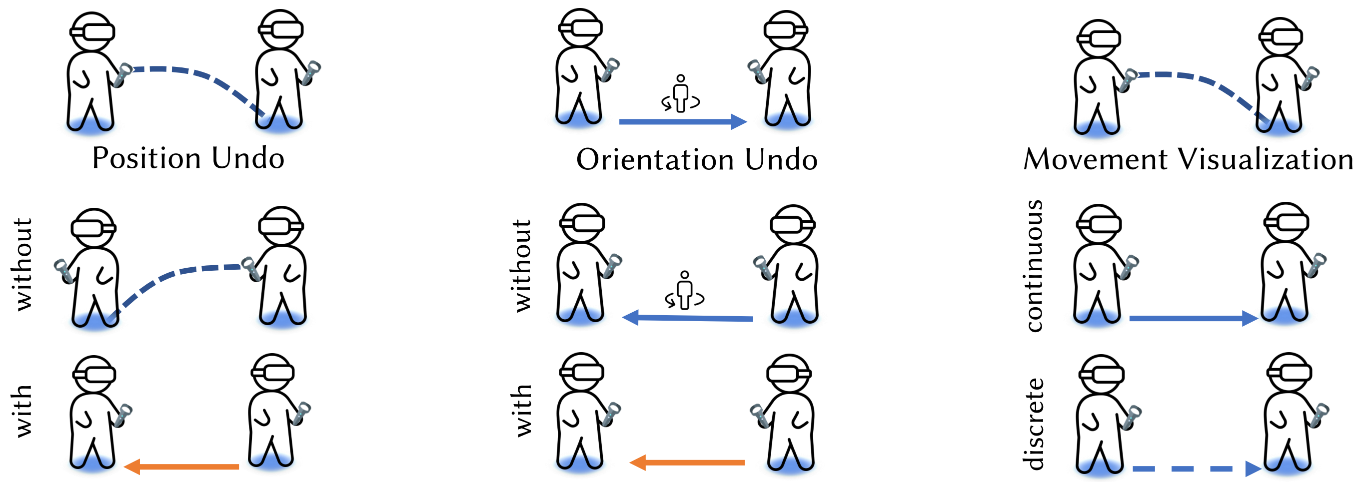


Figure 3: The independent variables studied in the experiment with their respective levels. From left to right: POSITION UNDO (WITHOUT POSITION UNDO and WITH POSITION UNDO), ORIENTATION UNDO (WITHOUT ORIENTATION UNDO and WITH ORIENTATION UNDO) and MOVEMENT VISUALIZATION (CONTINUOUS and DISCRETE).

each corridor. The coin is not visible from the central room. At the beginning of each trial, the participants are placed in the center of the room. The trial now consists of two phases:

- **training phase** In the first phase, 4 randomly selected corridors are accessible while the doors leading to the other corridors are closed (see fig. 2b). The participant's task is to collect the coins from the corridors as quickly as possible by pulling the trigger while the controller is in close proximity to the coin.
- **experimental phase** After the last of the 4 directly accessible coins is collected, the four other doors open. In the second phase, the participants' task is to collect the remaining 4 coins (see fig. 2c).

We opted for this variation of the radial maze task because, by taking out the freedom to explore the arms at will, this variant shifts the focus away from search strategies toward spatial understanding and memory. Further, this particular version of a maze allows the generation of comparable yet different tasks over multiple repetitions.

3.1.2 Independent Variables. To assess a broad picture of the possible factors influencing efficiency, spatial understanding, and user experience of the interaction, we varied 3 independent variables:

- **POSITION UNDO** Following our general idea, we varied the ability to undo a locomotion step between WITH POSITION UNDO and WITHOUT POSITION UNDO as our first independent variable. In the WITH POSITION UNDO conditions, pressing the action button one time would teleport the participant to the last waypoint. Repeated usage of the action traces the participant's movement path further back, one waypoint at a time.
- **ORIENTATION UNDO** Considering the literature review, we expected that the handling of the user's orientation during the reset would impact the performance parameters. Therefore, we varied the ability to undo orientation changes between WITH ORIENTATION UNDO and WITHOUT ORIENTATION UNDO as the second independent variable. In the WITH ORIENTATION UNDO conditions, pressing the action button resets the participant's orientation to the orientation captured at the beginning of the last teleport. More precisely, the keypress resets the orientation based on the participant's line of sight (that is, the orientation of the head-mounted display (HMD)). As with the POSITION UNDO, repeated usage of the action traces back to the previous waypoints of the participant.
- **MOVEMENT VISUALIZATION** We hypothesized that undo actions could result in reduced spatial orientation. As a possible solution, we varied the visualization of movement between DISCRETE and CONTINUOUS as a third independent variable. In DISCRETE visualization, the user's view is faded to black and then faded back in at the new position, resulting in no visual cues about the traveled path. This is the default visualization for teleport techniques in use today. On the other hand, the CONTINUOUS visualization quickly changes the user's viewpoint over time and thus provides a visual flow during the movement, as proposed by Bhandari et al. [5]. The authors demonstrated that this visualization can help to reduce spatial disorientation in teleport-based locomotion. To keep the conditions comparable, we used the respective visualization for all types of movement, i.e., for regular (forward) teleportations and undo actions for both position and orientation changes.

We varied our independent variables in a repeated-measures design, resulting in a total of $2 \times 2 \times 2 = 8$ conditions. In each condition, the participants performed the task as described above two times. As we only evaluate the four coins in the experimental phase, this yielded a total of $8 \times 4 \times 2 = 64$ trials per participant. To avoid learning effects, we counterbalanced the order of conditions in a balanced Latin square design with 8 levels. In addition, we chose a random distribution of initially closed corridors for training phase and randomized the coin's position in the left or right T arm.

3.1.3 Dependent Variables. To answer our research questions, we logged the following dependent variables for each trial in the experimental phase.

- **COIN COLLECTION TIME** as the time (in s) required to collect the coin. We started the timer with the collection of the previous coin.
- **NUMBER OF TELEPORTS** as the number of teleports (forward) used to reach the coin.
- **NUMBER OF MOVEMENT ACTIONS** as the total number of movement actions (teleport and undo) used to reach a coin.
- **TRAVELED DISTANCE** as the traveled distance (in m) to reach the coin.
- **TIME BEFORE FIRST CORRIDOR** as the time (in s) between starting training phase and the participant entering the first corridor.
- **REVISIT ERROR** as the number of visits to corridors that were already visited before. We counted the visit to a corridor as soon as the participant's position crossed the door threshold.

We reset all measurements when collecting a coin. Thus, all measurements refer to the path from one coin to the next, i.e., from the end of one corridor to the end of another. This includes the first coin of experimental phase since it was preceded by the last coin of training phase. We only analyzed the four coins from experimental phase. In addition, after each condition, we asked participants to complete a questionnaire that included the following.

- **TLX** as the NASA Task Load Index questionnaire as proposed by Hart and Staveland [31] to assess the perceived workload of participants.
- **SSQ** as the Simulator Sickness Questionnaire questionnaire as proposed by Kennedy et al. [33] to assess sickness induced by our interaction techniques.
- **PRESENCE** as the participants' self-assessment for their feeling of presence. For this, participants answered the question "In the computer-generated world I had a sense of 'being there'" on a 7-point Likert scale ("not at all" . . . "very much") as proposed by Slater et al. [58].
- **CUSTOM QUESTIONNAIRE** Additionally, we asked the participants to answer questions on a 5-point Likert scale, assessing their user experience.

3.2 Study Setup and Apparatus

We implemented the radial maze using Unity 2021.3.4f1. The central room was round with a diameter of 10 m. Each of the eight corridors was 15 m long and 3.8 m wide. Further, each corridor branched at the end with a T-junction (angle ±90°) into two corridors, each 5 m long and 3.8 m wide. The room was 3.5 m heigh and open to the top. The corridors were arranged in a circular pattern around the central room with relative angles of ±45° (see figs. 2a to 2c). The room layout provided no visual cues to the participant's current orientation. We visualized the rewards as spherical coins with a diameter of 0.2 m floating at the participants' shoulder height of around 1.4 m and 1 m away from the end of the T arms. Participants collected coins by pressing the trigger button in close physical proximity to a coin (0.2 m). In addition to the coin disappearing, we added an auditory signal communicating the successful collection.

We calibrated the maximum teleport and undo distance as 10 m. For DISCRETE, we chose the default values of SteamVR (0.2 s, fade to black and back) for both teleport and undo. For CONTINUOUS, we chose a motion speed of 10 m/s. Further, we implemented a study client to control the study. Using an external monitor, we could further monitor the participants' actions. The study client logged the dependent variables to CSV files.

We deployed the application to a Gaming Laptop with Intel Core i7-9750H CPU @ 2.60GHz, 16GB RAM, and an NVIDIA GeForce RTX 2070. The participants wore a HTC Vive Pro and interacted with the default HTC Vive controller in their dominant hand. The size of the calibrated tracking area was $2.7x2$ m. While participants were free to move, both POSITION UNDO and ORIENTATION UNDO effectively overwrote intermediate user movements since the last teleport. To preserve the consistency of the virtual and the physical world, we did not include the hand position in the undo. Accordingly, the relative position of the hand to the user's perspective remained the same after undo.

3.3 Procedure

After welcoming the participants, we introduced them to the concept. Then, we asked them to fill out a consent form together with a demographics questionnaire. We then described to the participants the exact procedure of the experiment and their task in the 8-arm radial maze, as well as the two experimental phases. After the participants could ask questions and we were confident that their task was clear to them, we started the first condition.

We told the participants the combination of ORIENTATION UNDO, POSITION UNDO, and MOVEMENT VISUALIZATION and started the system. In the following, participants had 2 min to acclimatize with the locomotion method before we started the actual task. To start the first phase, the system placed the participants in the center of the central room with 4 doors closed. Once ready, the participants started a visual timer (3 s) by pulling the trigger button. When the timer expired, the training phase began. After participants collected the fourth coin, the remaining 4 doors opened without further cue. Since the participants were in a T-side arm at this point, this happened invisibly. Immediately after and without pause, the experimental phase started, in which the participants collected the remaining 4 coins. The system then enforced a 1 min pause before the first repetition followed the described procedure.

After completing all two repetitions of the condition, we asked participants to remove the VR goggles and complete the questionnaires on a tablet. We enforced a 5 min break before starting the next condition. During this break, we asked the participants for further qualitative feedback in a semi-structured interview. Each experiment took about 100 minutes per participant. All participants and the investigator were vaccinated and anti-gen tested on the same day. Only the investigator and the participant were in the room at any given time. The investigator and participants wore medical face masks throughout the experiment. We disinfected all touched surfaces between the participants and ventilated the room for 30 minutes. Our institutional ethics board reviewed and approved the study design.

3.4 Participants

We recruited 24 participants (5 identified as female, 19 as male) aged between 20 and 34 ($\mu = 26.5$, $\sigma = 3.72$) from our university. 3 participants reported that they were first-time VR users, 15 reported that they had used VR before, and 6 reported that they were regular VR users. Participants received compensation of around 15$ in local currency.

3.5 Analysis

We performed 3-way repeated measures (RM) ANOVAs with the ORIENTATION UNDO, POSITION UNDO, and MOVEMENT VISUALIZATION as factors. For this, we first tested the data for violations of normality and sphericity assumptions using Shapiro-Wilk's and Mauchly's tests, respectively. If the assumption of normality was violated, we performed a non-parametric analysis. If the assumption of sphericity was violated, we corrected the tests using the Greenhouse-Geisser method and report the ϵ. When the (RM) ANOVAs reported significant effects, we applied Bonferroni-corrected t-tests for post-hoc analysis. For the multi-factorial analysis of non-parametric data, such as the Likert questionnaires, we performed an Aligned Rank Transform (ART) as proposed by Wobbrock et al. [67] and applied the ART-C procedure as proposed by Elkin et al. [22] for post-hoc analysis. Further, we report the generalized eta-squared η_G^2 as an estimate of the effect size. As suggested by Bakeman [3], we classify these effect sizes using Cohen's suggestions [17] as small ($> .0099$), medium ($> .0588$), or large ($> .1379$). For count data, such as the number of teleports and errors, we fitted Poisson regression models and applied Type III Wald chi-square tests for significance testing.

4 RESULTS

In the following section, we report the results structured around the dependent variables described in section 3.

4.1 Coin Collection Time

To assess the efficiency of participants, we measured the time needed to collect a coin. We found significantly shorter coin-collection times for DISCRETE compared to CONTINUOUS with measured coin collection times ranging from $M = 13.0$ s, $SD = 9.4$ s (both, discrete) to $M = 20.5$ s, $SD = 12.3$ s (orientation only, continuous), see fig. 4a.

We found a significant ($F_{1,23} = 25.42$, $p < .001$) influence of the MOVEMENT VISUALIZATION with a medium ($\eta_G^2 = 0.12$) effect size. Post-hoc tests confirmed significantly ($p < .001$) shorter coin-collection times for DISCRETE ($M = 13.7$ s, $SD = 8.2$ s) compared to CONTINUOUS ($M = 18.7$ s, $SD = 10.7$ s). We could not find significant main effects of the POSITION UNDO ($F_{1,23} = .83$, $p > .05$) or the ORIENTATION UNDO ($F_{1,23} = 2.35$, $p > .05$) nor interaction effects.

To exclude the influence of the different speeds in the two visualizations, we additionally analyzed the coin-collection time with the time for the actual teleports removed. We found coin-collection times ranging from $M = 10.7$ s, $SD = 6.8$ s (no undo, continuous) to $M = 14.4$ s, $SD = 13.3$ s (orientation only, continuous). We could not find significant main effects of MOVEMENT VISUALIZATION ($F_{1,23} = 0.57$, $p > .05$), POSITION UNDO ($F_{1,23} = 1.84$, $p > .05$) or ORIENTATION UNDO ($F_{1,23} = 4.22$, $p > .05$) nor any interaction effects.

4.2 Number of Teleports

As another measurement of efficiency, we measured the number of teleports used to reach a coin. We found significantly higher numbers of teleports WITHOUT POSITION UNDO and WITH ORIENTATION UNDO with mean numbers of teleports ranging from $M = 5.1$, $SD = 4.0$ (positioin only, continuous) to $M = 9.9$, $SD = 5.4$ (no undo, discrete), see fig. 4b.

The analysis revealed a significant ($\chi^2(1) = 75.37$, $p < .001$) main effect for the POSITION UNDO. Post-hoc tests confirmed significantly ($p < .001$) higher numbers of teleports for WITHOUT POSITION UNDO ($M = 9.5$, $SD = 5.2$) compared to WITH POSITION UNDO ($M = 6.0$, $SD = 6.1$). Further, we found a significant ($\chi^2(1) = 7.26$, $p < 0.01$) main effect of the ORIENTATION UNDO on the number of teleports. Post-hoc tests confirmed significantly ($p < .01$) higher numbers of teleports WITH ORIENTATION UNDO ($M = 7.8$, $SD = 5.7$) compared to WITHOUT ORIENTATION UNDO ($M = 7.7$, $SD = 6.1$). We could not find a significant main effect for the MOVEMENT VISUALIZATION ($\chi^2(1) = 0.39$, $p > .05$).

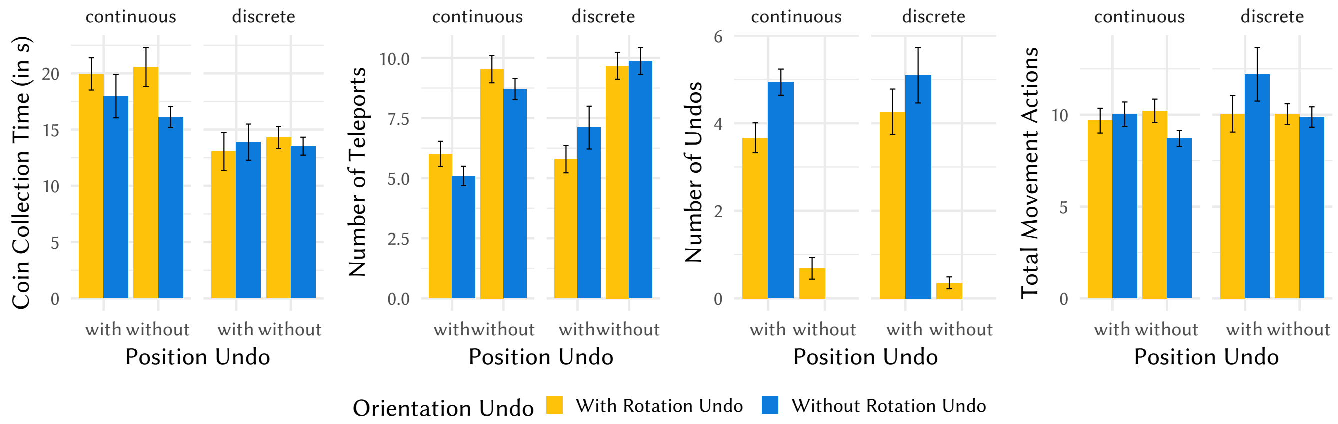
Besides the main effects, we found a significant ($\chi^2(1) = 19.44$, $p < .001$) interaction effect between ORIENTATION UNDO and MOVEMENT VISUALIZATION. While we could not find a difference in the number of teleports between DISCRETE and CONTINUOUS for WITH ORIENTATION UNDO ($M = 7.7$, $SD = 5.9$ and $M = 7.8$, $SD = 5.6$, $p > .05$), there was a significant ($p < .001$) difference for WITHOUT ORIENTATION UNDO (DISCRETE: $M = 8.5$, $SD = 7.4$ CONTINUOUS: $M = 6.9$, $SD = 4.5$).

4.3 Number of Undo Actions

To gain a deeper understanding of the usage of undo actions to reach a target, we analyzed the number of undo actions used to reach a target. We found that the type of undo support available had the strongest impact on the usage, with orientation-only support rarely used. We found a wide spread of usage numbers, ranging from $M = 0.4$, $SD = 1.3$ (orientation only, discrete) to $M = 5.1$, $SD = 6.2$ (position only, discrete), see fig. 4c.

For the analysis, we removed the data for the no undo conditions, considering the undo types (position-only, orientation-only, and both) as levels of a single factor. We found a significant ($\chi^2(2) = 226.88$, $p < .001$) main effect on the number of undo actions. Post-hoc tests confirmed significant differences between all groups (orientation-only: $M = 0.5$, $SD = 2.0$, both: $M = 4.0$, $SD = 4.3$ and position-only: $M = 5.0$, $SD = 4.8$, all $p < .001$). Further, the analysis revealed a significant ($\chi^2(1) = 4.28$, $p < .05$) main effect of the MOVEMENT VISUALIZATION. Post-hoc tests indicated significantly higher numbers of undo actions for discrete ($M = 3.2$, $SD = 5.1$) compared to continuous ($M = 3.1$, $SD = 3.4$).

Finally, we found a significant ($\chi^2(2) = 13.45$, $p < .01$) interaction effect between undo type and MOVEMENT VISUALIZATION. The analysis did not indicate significant differences between DISCRETE and CONTINUOUS for the position-only and both conditions. For the orientation-only conditions, however, the analysis showed significantly higher usage for CONTINUOUS ($M = 0.7$, $SD = 2.4$) compared to the DISCRETE ($M = 0.4$, $SD = 1.3$), $p < .05$. Nevertheless, the usage was still significantly lower compared to all other combinations (all $p < .001$).



(a) Coin Collection Time **(b) Number of Teleports** **(c) Number of Undos** **(d) Total Movement Actions**

Figure 4: coin collection time (a), number of teleports (b), number of undos (c) and number of movement actions (d). Error bars depict the standard error.

4.4 Streak Length

We analyzed the number of successive actions of the same movement type (teleport and undo) as the streak length. We found comparable streaks between teleport and undo for the position-only and both conditions. For orientation-only, we found significantly shorter streak lengths for undo. Overall, we found streak lengths ranging from $M = 3.8$, $SD = 2.6$ (positioin only, continuous) to $M = 9.5$, $SD = 2.8$ (no undo, discrete) for teleport. For undo, we found streak lengths ranging from $M = 2.9$, $SD = 2.2$ (orientation only, discrete) to $M = 4.6$, $SD = 2.5$ (positioin only, continuous).

We excluded the conditions with no undo support, as the streak length would total the number of teleports. We found a significant ($\chi^2(3) = 78.47$, $p < .001$) main effect of the available undo support. While we found longer mean streak lengths for orientation-only conditions ($M = 7.9$, $SD = 3.6$) compared to both other movement types (position only: $M = 4.6$, $SD = 4.3$, both: $M = 4.2$, $SD = 2.6$), post-hoc tests did not confirm significant differences.

Further, we found a significant ($\chi^2(2) = 28.99$, $p < .001$) interaction effect between the available undo support and the movement type (i.e., teleport and undo). We could not find significant differences between the streak lengths between teleport and undo for the position-only (teleport: $M = 4.6$, $SD = 4.4$, undo: $M = 4.5$, $SD = 4.3$) and both (teleport: $M = 4.7$, $SD = 2.9$, undo: $M = 3.7$, $SD = 2.1$) conditions. For the orientation-only conditions, however, we found significantly longer teleport streaks ($M = 9.1$, $SD = 2.6$) compared to the undo streaks ($M = 3.0$, $SD = 3.0$).

4.5 Total Movement Actions

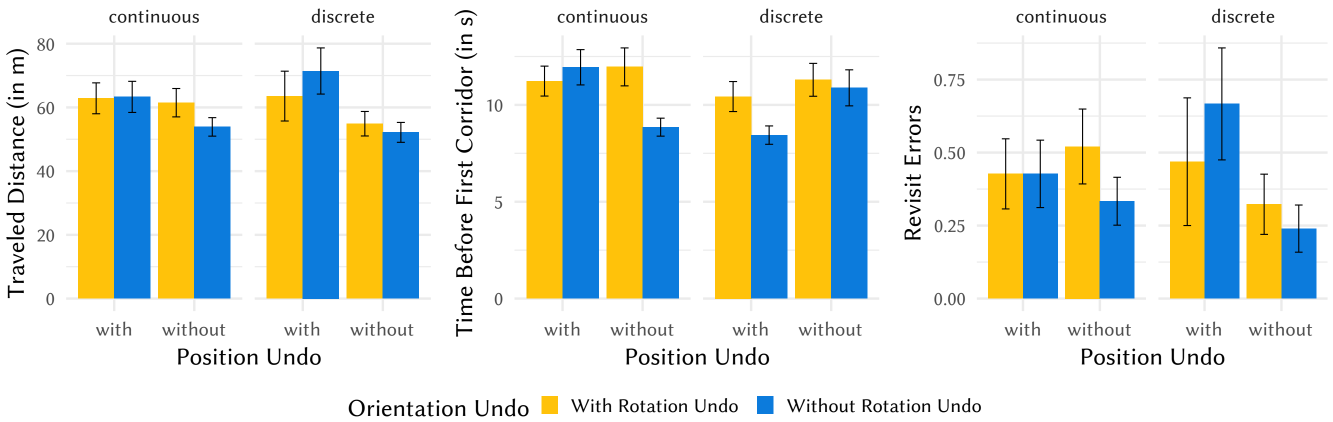
We further analyzed the number of total movement actions as the sum of teleport and undo movements used to reach a coin. The analysis indicated no main effects but showed interaction effects between position undo and orientation undo and movement visualization and orientation undo, respectively, which we detail below. We found mean numbers ranging from $M = 8.7$, $SD = 4.2$ (no undo, continuous) to $M = 12.2$, $SD = 14.2$ (position only, discrete), see fig. 4d.

While the analysis did not indicate any main effects (movement visualization: $\chi^2(1) = .69$, $p > .05$, position undo: $\chi^2(1) = 1.42$, $p > .05$ and orientation undo: $\chi^2(1) = .61$, $p > .05$), we found significant interaction effects between the independent variables. First, we found a significant ($\chi^2(1) = 8.87$, $p < .01$) interaction effect between position undo and orientation undo. While we could not find a difference in the number of total movement actions between both levels of position undo with orientation undo (with position undo: $M = 9.9$, $SD = 8.3$ without position undo: $M = 10.1$, $SD = 5.9$), we found significantly ($p < .001$) higher numbers of movement actions with position undo ($M = 11.1$, $SD = 11.1$) compared to without position undo ($M = 9.3$, $SD = 4.9$) without orientation undo.

We found a significant ($\chi^2(1) = 6.20$, $p < .05$) interaction effect between movement visualization and orientation undo. We we could not find differences for discrete ($M = 10.0$, $SD = 7.9$) and continuous ($M = 10.0$, $SD = 6.4$) with orientation undo, $p > .05$. without orientation undo, however, we found significantly ($p < .001$) higher numbers for discrete ($M = 11.0$, $SD = 10.8$) compared to continuous ($M = 9.4$, $SD = 5.5$).

4.6 Traveled Distance

We analyzed the traveled distance as another measure of efficiency.We found distances ranging from $M = 52.2$ m, $SD = 30.6$ m (no undo, discrete) to $M = 71.4$ m, $SD = 71.0$ m (position only, discrete), see fig. 5a. The analysis revealed a significant ($F_{1,23} = 7.69$, $p < .05$) main effect of the position undo on the traveled distance with a small ($\eta_G^2 = 0.04$) effect size. Post-hoc tests confirmed significantly ($p < .05$) higher traveled distances with position undo ($M = 65.3$ m, $SD = 62.0$ m) compared to without position undo ($M = 55.6$ m, $SD = 35.6$ m). We could not find other main (movement visualization: $F_{1,23} = 0.24$, $p > .05$, orientation undo: $F_{1,23} = 0.00$, $p > .05$) or interaction effects.



(a) Traveled Distance **(b) Time Before First Corridor** **(c) Revisit Errors**

Figure 5: TRAVELED DISTANCE (a), TIME BEFORE FIRST CORRIDOR (b) and REVISIT ERROR (c). Error bars depict the standard error.

4.7 Time Before First Corridor

We measured the time before entering the first corridor to understand how closely they tried to memorize the surroundings. The analysis indicated an interaction effect between MOVEMENT VISUALIZATION and POSITION UNDO with lower times for the discrete visualization WITH POSITION UNDO. Overall, we found times ranging from $M = 8.4$ s, $SD = 4.7$ s (position only, discrete) to $M = 12.0$ s, $SD = 9.6$ s (orientation only, continuous), see fig. 5b.

While the analysis did not reveal any main effects (MOVEMENT VISUALIZATION: $F_{1,23} = 1.34$, $p > .05$, POSITION UNDO: $F_{1,23} = 0.23$, $p > .05$, ORIENTATION UNDO: $F_{1,23} = 1.40$, $p > .05$), we found an interaction effect.

The analysis revealed a significant ($F_{1,23} = 12.50$, $p < .01$) interaction effect between MOVEMENT VISUALIZATION and POSITION UNDO with a small ($\eta^2_G = 0.006$) effect size. For WITHOUT POSITION UNDO, the analysis did not indicate a significant difference between both levels of MOVEMENT VISUALIZATION (CONTINUOUS: $M = 10.4$ s, $SD = 7.7$ s, DISCRETE: $M = 11.1$ s, $SD = 8.7$ s). For WITH POSITION UNDO, however, we found a more pronounced, yet not significant, difference with lower times for discrete (CONTINUOUS: $M = 11.6$ s, $SD = 8.3$ s, DISCRETE: $M = 9.4$ s, $SD = 6.4$ s).

4.8 Revisit Error

We logged the number of revisits to previously explored corridors as a measure of (dis-) orientation. We found significantly higher numbers of errors WITH POSITION UNDO. Further, we found interaction effects between the independent variables, which we detail below. Overall, we found error rates per collected coin ranging from $M = 0.2$, $SD = 0.8$ (no undo, discrete) to $M = 0.7$, $SD = 1.9$ (position only, discrete), see fig. 5c.

The analysis indicated a significant ($\chi^2(1) = 7.89$, $p < .01$) main effect of the POSITION UNDO on the number of errors. Post-hoc tests confirmed significantly ($p < .01$) higher numbers of errors for WITH POSITION UNDO ($M = 0.5$, $SD = 1.6$) compared to WITHOUT POSITION UNDO ($M = 0.4$, $SD = 1.0$). We could not find significant main effects for MOVEMENT VISUALIZATION ($\chi^2(1) = 0.01$, $p > .05$) or ORIENTATION UNDO ($\chi^2(1) = 0.14$, $p > .05$).

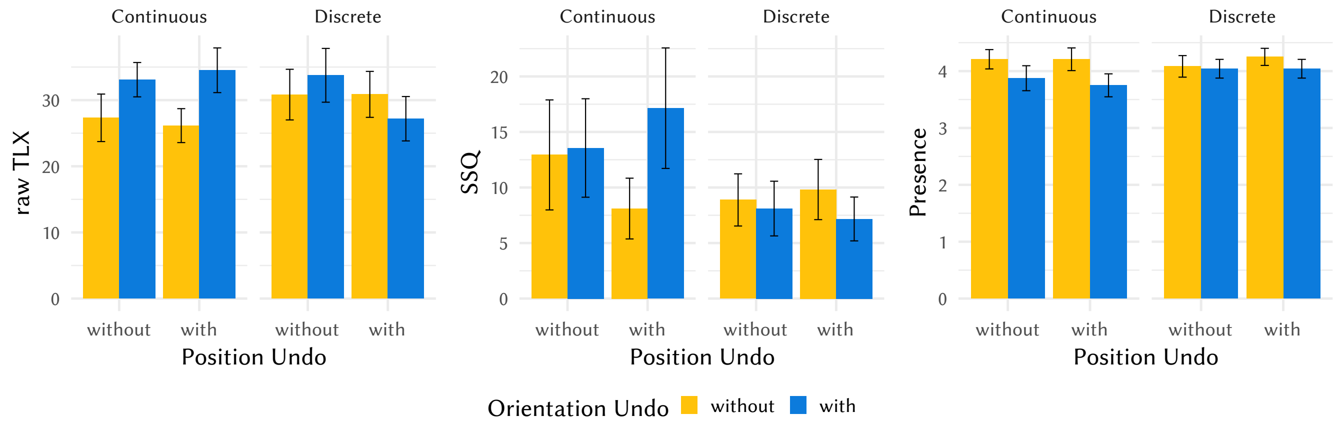
We found a significant ($\chi^2(1) = 5.67$, $p < .05$) interaction effect between POSITION UNDO and ORIENTATION UNDO. For WITH ORIENTATION UNDO, we found no significant difference WITH POSITION UNDO ($M = 0.5$, $SD = 1.7$) and WITHOUT POSITION UNDO ($M = 0.4$, $SD = 1.1$), $p > .05$. For WITHOUT ORIENTATION UNDO, however, we found significantly ($p < .001$) higher numbers for WITH POSITION UNDO ($M = 0.6$, $SD = 1.6$) compared to WITHOUT POSITION UNDO ($M = 0.3$, $SD = 0.8$).

Finally, we found a significant ($\chi^2(1) = 8.56$, $p < .01$) interaction effect between POSITION UNDO and MOVEMENT VISUALIZATION. For the CONTINUOUS conditions, there was no significant difference between both levels of POSITION UNDO (WITH POSITION UNDO: $M = 0.4$, $SD = 1.2$, WITHOUT POSITION UNDO: $M = 0.4$, $SD = 1.1$), $p > .05$. For the DISCRETE conditions, however, we found significantly higher numbers of errors ($p < .001$) for WITH POSITION UNDO ($M = 0.6$, $SD = 2.0$) compared to WITHOUT POSITION UNDO ($M = 0.3$, $SD = 0.9$).

4.9 NASA Task Load Index

We assessed the NASA Task Load Index (TLX) as a measure of the perceived workload. We found significantly higher TLX values for WITH ORIENTATION UNDO with aggregated raw values ranging from $M = 26.1$, $SD = 12.6$ (positioin only, continuous) to $M = 34.5$, $SD = 16.6$ (both, continuous), see fig. 6a.

The analysis indicated a significant ($F_{1,23} = 4.64$, $p < .05$) main effect of ORIENTATION UNDO on the TLX. Post-hoc tests confirmed significantly ($p < .05$) higher TLX values for WITH ORIENTATION UNDO ($M = 32.1$, $SD = 16.6$) compared to WITHOUT ORIENTATION UNDO ($M = 28.8$, $SD = 16.5$). We could not find further main (MOVEMENT VISUALIZATION: $F_{1,23} = 0.03$, $p > .05$, POSITION UNDO: $F_{1,23} = 0.56$, $p > .05$) or interaction effects.



(a) NASA Task Load Index

(b) Simulator Sickness Questionnaire

(c) Presence

Figure 6: The mean results of the (a) TLX, (b) SSQ and (c) PRESENCE. All error bars depict the standard error.

4.10 Simulator Sickness Questionnaire

We assessed the Simulator Sickness Questionnaire (SSQ) to assess the influences of our proposed interaction techniques on the experienced simulator sickness. We found significantly higher SSQ values for WITH ORIENTATION UNDO as well as an interaction effect between ORIENTATION UNDO and MOVEMENT VISUALIZATION, which we detail below. Overall, we found mean values ranging from $M = 7.2$, $SD = 9.7$ (both, discrete) to $M = 17.1$, $SD = 26.6$ (both, continuous), see fig. 6b.

Shapiro-Wilk's test indicated a violation of the assumption of normality of the residuals. Therefore, we analyzed the data using the Aligned Rank Transform approach as outlined in section 3.5. The ART ANOVA indicated a significant ($F_{1,23} = 5.95$, $p < .05$) main effect for ORIENTATION UNDO with a large ($\eta_G^2 = 0.21$) effect size. Post-hoc tests confirmed significantly ($p < .05$) higher SSQ scores for WITH ORIENTATION UNDO ($M = 11.5$, $SD = 19.0$) compared to WITHOUT ORIENTATION UNDO ($M = 9.9$, $SD = 16.3$). We could not find further main effects (MOVEMENT VISUALIZATION: $F_{1,23} = 0.24$, $p > .05$, POSITION UNDO: $F_{1,23} = 2.18$, $p > .05$).

Further, we found a significant ($F_{1,23} = 11.62$, $p < .01$) interaction effect between ORIENTATION UNDO and MOVEMENT VISUALIZATION. We did not find significant differences in the SSQ scores for both levels of ORIENTATION UNDO for the DISCRETE visualization (WITHOUT ORIENTATION UNDO: $M = 9.4$, $SD = 12.3$, WITH ORIENTATION UNDO: $M = 7.6$, $SD = 10.8$), $p > .05$. For CONTINUOUS, however, we found significantly ($< .05$) higher SSQ scores for WITH ORIENTATION UNDO ($M = 15.3$, $SD = 24.1$) compared to WITHOUT ORIENTATION UNDO ($M = 10.5$, $SD = 19.5$).

4.11 Presence

We assessed the participants' feeling of presence through the answer to the question "In the computer-generated world I had a sense of 'being there'" on a 7-point Likert scale ("1: not at all" . . . "7: very much"). We found significantly higher presence ratings for WITHOUT ORIENTATION UNDO with answers ranging from $M = 3.8$, $SD = 1.0$ (both, continuous) to $M = 4.3$, $SD = 0.7$ (position only, discrete), see fig. 6c.

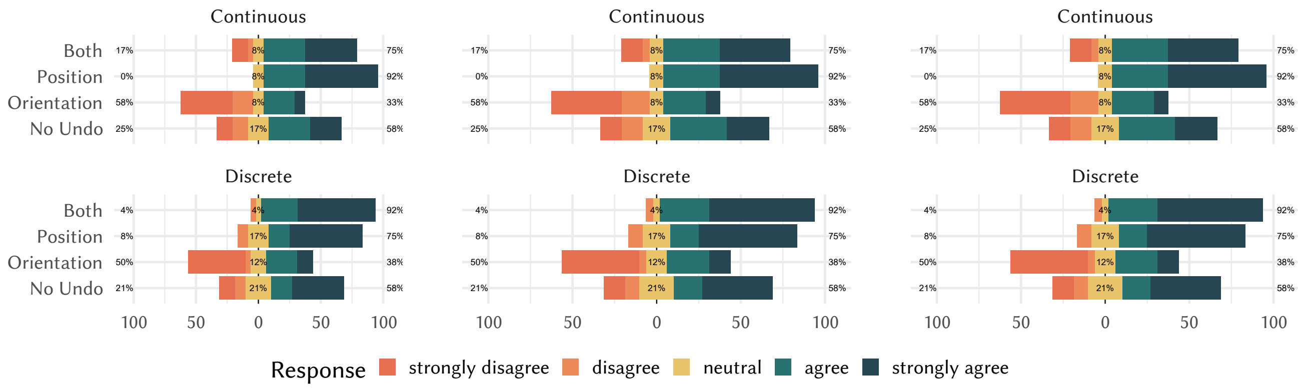
The ART ANOVA revealed a significant ($F_{1,23} = 20.88$, $p < .001$) main effect for the ORIENTATION UNDO on the participants' ratings of the presence statement with a large ($\eta_G^2 = 0.48$) effect size. Post-hoc tests confirmed significantly higher presence ratings for WITHOUT ORIENTATION UNDO ($M = 4.2$, $SD = 0.9$) compared to WITH ORIENTATION UNDO ($M = 3.9$, $SD = 0.9$). We could not find any other significant main (MOVEMENT VISUALIZATION: $F_{1,23} = 0.74$, $p > 0.5$, POSITION UNDO: $F_{1,23} = 0.02$, $p > .05$) or interaction effects.

4.12 Custom Questionnaire

As a last measure, participants answered three custom questions on a 5-point Likert scale. In the following section, we analyze their answers.

"The locomotion technique helped me complete my task." We found a significant ($F_{1,23} = 73.80$, $p < .001$) influence of the POSITION UNDO on the participants' answers with a medium ($\eta_G^2 = 0.09$) effect size. Post-hoc tests confirmed significantly ($p < .001$) higher ratings for WITH POSITION UNDO compared to WITHOUT POSITION UNDO. Further, we found a significant ($F_{1,23} = 12.33$, $p < .01$) influence of the ORIENTATION UNDO with a large ($\eta_G^2 = 0.21$) effect size. Post-hoc tests confirmed significantly ($p < .01$) higher ratings for WITHOUT ORIENTATION UNDO compared to WITH ORIENTATION UNDO. Finally, we found a significant ($F_{1,23} = 17.30$, $p < .001$) interaction effect between POSITION UNDO and ORIENTATION UNDO. The combination with WITH ORIENTATION UNDO was rated significantly ($p < .001$) less helpful compared to WITHOUT ORIENTATION UNDO for WITHOUT POSITION UNDO. For WITH POSITION UNDO, however, the effect was turned upside down, and participants rated the combination with WITH ORIENTATION UNDO significantly ($p < .001$) more helpful compared to WITHOUT ORIENTATION UNDO. Figure 7a shows all answers from our participants.

"The locomotion technique was convenient to use." We found significant main effects for all three independent variables (POSITION UNDO: $F_{1,23} = 35.43$, $p < .001$ with a medium ($\eta_G^2 = 0.08$) effect size, ORIENTATION UNDO: $F_{1,23} = 25.28$, $p < .001$ with a large ($\eta_G^2 = 0.21$) effect size and MOVEMENT VISUALIZATION: $F_{1,23} = 14.55$, $p < .001$



(a) Helpfulness **(b) Convenience** **(c) Orientation Problems**

Figure 7: The participants' answers to our questions on a 5-point Likert scale regarding the perceived (a) helpfulness, (b) convenience and (c) orientation problems. For full questions, please refer to the text.

with a small ($\eta_G^2 = 0.01$)). Post-hoc tests confirmed significantly (all $p < .001$) higher ratings for with position undo, without orientation undo and discrete compared to their respective counterparts. Further, we found interaction effects. First, we found a significant ($F_{1,23} = 8.10$, $p < .01$ interaction effect between position undo and orientation undo with a medium ($\eta_G^2 = 0.13$) effect size. For without position undo, we found that participants rated the convenience significantly lower for with orientation undo compared to without orientation undo ($p < .01$). For with position undo, however, participants found with orientation undo significantly more convenient compared to without orientation undo ($p < .001$). Finally, we found a significant ($F_{1,23} = 22.44$, $p < .001$) interaction effect between orientation undo and movement visualization with a large ($\eta_G^2 = 0.34$) effect size. For continuous, with orientation undo was rated significantly ($p < .001$) lower compared to without orientation undo. For discrete, however, we found the opposite effect and better ratings for with orientation undo. Yet, the difference was not significant ($p > .05$). Figure 7b shows all answers from our participants.

"I had problems orienting myself." For the last question, the analysis did not indicate any main effects in the data (position undo: $F_{1,23} = 2.36$, $p > .05$, orientation undo: $F_{1,23} = 2.62$, $p > .05$ and movement visualization: $F_{1,23} = 0.28$, $p > .05$). However, we found a significant ($F_{1,23} = 5.37$, $p < .05$) interaction effect between orientation undo and movement visualization with a large ($\eta_G^2 = 0.34$) effect size. For discrete, we participants reported significantly higher levels of orientation-loss for without orientation undo compared to with orientation undo ($p < .05$). For continuous, however, we found that participants reported higher levels of orientation-loss for with orientation undo compared to without orientation undo. Yet, the difference was not significant ($p > .05$). Figure 7c shows all answers from our participants.

4.13 Qualitative Feedback

In general, our participants showed strong approval for the idea of reverting locomotion steps through undo actions.

In particular, the position undo was positively received by 22 of the 24 participants. Asked for the reasons, participants reported that position undo was "*convenient*" (P5, P16) and "*helpful*" (P6) as there was "*no need to turn]*" (P4) which made it "*quicker to navigate back [...] without having to physically turn around*" (P3). This helped to "*[not] lose your orientation so easily.*" (P21). Further, participants commented that it is "*nice to have when doing errors*" (P11)

Regarding the orientation undo, participants' opinions were split, with 13 out of the 24 participants preferring to have orientation support. Participants described their experiences with orientation undo as "*faster [than physically turning back]*" (P6) and "*helpful*" (P5, P8) as "*it helps to establish a familiar starting position*" (P7). In contrast, other participants reported that it "*made me lose orientation*" (P17) by causing "*irritation in my sense of space*" (P2). Further, participants reported increased cybersickness as it "*made motion sickness worse*" (P11) and "*just made me dizzy and feel disconnected*" (P12). To explain this mismatch between the positive and negative aspects, P18 explained that it depends on what level of position undo it was paired with: "*[orientation support] messed up my orientation. Except when combined with position undo*" (P18). Other participants agreed as "*orientation reset [...] without position reset felt [...] useless.*" (P10) while it was considered "*helpful*" (P9, P10, P16) when used "*together*" (9) and in "*combination*" (P1, P10, P16, P18) with position undo.

The question about the preferred movement visualization again showed a mixed picture, with a clear tendency towards discrete visualization. While 6 participants preferred continuous, the other 18 saw advantages in the discrete visualization. Asked for the reasons for preferring the discrete visualization, participants explained that it felt "*faster*" (P1, P3, P5, P6, P8, P9, P10, P21, P22) and caused "*less vertigo*" (P3) and "*less nausea*" (P8, P22). The

CONTINUOUS visualization was found to provide "*better orientation*" (P2, P4) and a "*greater immersion in the virtual world*" (P7) which "*helped [..] with orientation*" (P15). As a possible reason, P20 explained that "you can see the route you are traveling".

5 DISCUSSION

The results of our controlled experiment suggest that undo actions provide a viable addition to point&teleport. We found that undo actions can increase the efficiency of participants when locomoting in virtual environments and received very favorable feedback from our participants. However, we also found a negative impact on the participants' ability to orientate themselves. In the following section, we discuss the results in relation to our research questions.

5.1 Position Undo Allows for Faster Travel but Increases Errors

In our analysis, we found significantly higher numbers of errors, which required participants to perform a higher number of teleports and, subsequently, higher traveled distances to collect a coin WITH POSITION UNDO. Surprisingly, this increased movement of the participants was not reflected in the time used to collect a coin. We found no significant effect of position undo on time required and even the lowest average time measured for a condition with position undo (both, discrete).

We attribute this finding to a combination of several effects. First, the cost (in terms of distance covered per time) for undo actions is lower than for standard locomotion actions. This is explained by the ability to travel a distance comparable to a normal teleport with a simple button press, requiring no prior physical body rotation and no targeting. Due to the radial maze design of the task, about half of all distances in the WITH POSITION UNDO conditions could be covered by jumping back as participants had to return to the central room on their way to the next coin. Second, while we found no negative influence on participants' orientation in their subjective self-assessment that could explain the increased error rates, we found evidence that the lower cost for undo actions contributed to this. The participant's task was to collect the coins as quickly as possible. Using the radial arm maze task, we sought to increase the time cost of a circular search to encourage participants to rely on their orientation in the search rather than visiting all paths sequentially. Looking at our results, however, we hypothesize that by reducing the effort to travel back through undo actions, participants paid less attention to preventing errors and perceived it as more efficient to check the corridors one after the other. This increased the error rate but resulted in comparable times due to the inherently faster movement. The data from our participants supports this interpretation, as they rated WITH POSITION UNDO as significantly more convenient and helpful in completing the task. In addition to the quantitative results, the qualitative feedback supports this interpretation as participants reported that undo support helped resolve errors.

5.2 Orientation Undo Alone Has a Negative Effect but Can Enhance the Positive Characteristics of Position Undo.

As position undo, ORIENTATION UNDO significantly increased the number of errors and, consequently, the number of teleports and the distance traveled per coin. But, again, these increased travel distances did not result in increased coin-collection times. Further, we found a negative effect on the TLX, the SSQ, and the perceived presence. However, these individual results do not provide the complete picture. In combination with WITH POSITION UNDO, orientation undo reduced the number of errors and was rated significantly more convenient and helpful than without orientation undo. This finding is reinforced by the qualitative feedback, where most participants preferred orientation undo to no orientation undo, but only in combination with position undo. We, therefore, attribute many of the individual negative results of orientation undo to the poor performance of the technique without position undo.

The good performance of the combination of position and orientation undo appears intuitively understandable, given that both dimensions are reset in one step, resulting in the lowest cognitive load of the discrete techniques. Surprisingly, however, position-only undo without orientation worked comparably well across all measures, whereas orientation-only undo received poor ratings. Further, it was used much less: While participants used a similar number of teleports and undos in position-only and both conditions and the streak length also showed no differences, undo actions were used only very rarely in orientation-only conditions. While we do not have a conclusive explanation for this, we attribute this effect to the unique properties of motion in VR. Changing position in VR involves a relatively large amount of effort aiming with the controller. This intermediate step of aiming is omitted with positions undo. For orientation changes, however, users only need to turn their heads, which implies a lower effort. Accordingly, we hypothesize that our participants were more likely to accept the potential drawbacks of increased cognitive load from undo actions with position undo, while the benefits for orientation resets alone were too small to offset the drawbacks. Further work is needed in this area to conclude on these questions.

5.3 Prefer Discrete over Continuous Visualization

For the MOVEMENT VISUALIZATION, the discrete visualization in our experiment showed clear advantages over the continuous visualization in many ways. For example, the discrete visualization led to lower coin-collection times, reduced cybersickness, and was clearly preferred by the participants in both quantitative and qualitative feedback.

In particular, the continuous movement visualization was negatively evaluated with orientation undo. We attribute this effect to the increased mismatch between the virtual camera rotation and the lack of physical head rotation, increasing cybersickness and potentially affecting the other measures. This is supported by significantly higher levels of reported orientation loss with orientation undo in the continuous visualization conditions and predominantly negative feedback in the quantitative and qualitative feedback by the participants.

We acknowledge that some of the limitations found for the continuous visualization might be based on the implementation details, such as the duration, and other implementations might yield other results. However, we are confident that our results provide valuable insights into the design space of both discrete and continuous movement visualizations for undo actions.

5.4 How to Undo?

Taken together, our results support the use of undo actions compared to state-of-the-art, which we explored as a baseline (no undo, discrete) in the study. Further, while continuous movement and the single use of orientation undo did not translate into improvements in quantitative and qualitative data, we found strong support for position undo.

Our participants perceived position undo positively, and the quantitative data confirmed fast travel speeds (as distance traveled per time) with and without orientation support. Further, our data show that the undo options were frequently used in the position-only condition and in both conditions, although we left it up to participants to decide how they wanted to move. We found that the different movement options were often used in a series of 3-5 actions. This finding is consistent with our observations from the experiment: Participants teleported to a target required, on average, 3-5 teleports as they did not use the maximum teleport distance. After collecting the coin (or discovering a mistake), participants used a quick succession of position undo actions to return to the starting point, if available in the condition. The question of which of the options was performing and perceived better seemed to be largely based on user preferences in our controlled experiment.

Therefore, we propose to provide users with the option to revert their movements with position and (optionally) orientation in future VR experiences. However, a deeper investigation of the higher number of errors is needed in the future to explore whether the found rising number is an artifact introduced by the study task design or a consequence of the interaction technique.

6 LIMITATIONS AND FUTURE WORK

We are convinced that the presented concepts and results of our evaluation provide valuable insights and guidelines for the future use of undo actions for locomotion in VR environments. However, our experiment's design and results impose some limitations and directions for future work, which we discuss in the following.

6.1 Ecological Validity and Real-World Applicability

In this paper, we contributed an experiment that deliberately adopted a highly artificial and reduced virtual environment and task. We chose this approach to exclude external influencing factors (for example, landmarks in the world) and to assess the pure effect of the presented locomotion techniques on efficiency, orientation, and user experience. In particular, we wanted to measure the effects on users' orientation abilities without landmarks in the VR scene. These would have turned the task from a pure orientation task to a memory task.

In realistic VR scenarios, however, users will find spatial cues as landmarks in the virtual world. Previous work has shown that such spatial cues greatly impact users' orientation ability [30]. Such cues can, thus, help to mitigate the negative effects of some of the interaction techniques presented here on orientation ability while keeping the positive effect on efficiency. Future work in this area is needed to assess the influence of spatial cues and their interaction with the techniques presented. However, we are confident that our work can serve as a baseline for this.

6.2 Generalizability to Other Locomotion Techniques

In this work, we explored undo actions for virtual locomotion using various extensions to point&teleport. We chose this approach to study the impact of our extensions on the most commonly used interaction technique.

However, in recent years, research has brought forth a wide variety of other artificial locomotion techniques (see section 2.1), yielding different requirements and implications for the inclusion and design of undo actions. Although we are confident that the benefits of undo actions demonstrated in this work can also be applied to these techniques, further work is needed to investigate the impact of undo actions on efficiency, orientation, and user experience in these scenarios.

6.3 Undoing Time

This work explored the use of locomotion undo actions, undoing spatial changes while moving through the virtual environment. However, the known mental model for undo actions, as users know it from interaction with computer systems, describes something different: Here, an undo reverses an action as if it had never happened [1, 69]. In the picture of interaction in a VR world, not only the movement would be undone, but also the further actions in the world; in a way, it would be a rewinding of time. This rewinding of time has already been investigated for desktops [35, 56] and, recently, for VR scenarios [21].

While we find this approach highly intriguing and promising, we deliberately opted not to include a temporal undo in our design. This design decision is rooted in our work's specific intention to target the process of locomotion in VR. Therefore, the simultaneous undoing of time and, thus, the users' actions in the scene would effectively prevent this from being used as a locomotion technique, as any action (e.g., collecting a coin) would be undone at the same time.

6.4 Refinement of Undo Actions

In our work, we found a negative influence of undo actions on the number of errors, which we assessed as a measure of the users' spatial orientation. For our experiment, we investigated continuous visualization of the locomotion process as a possible way to strengthen spatial understanding. However, we found negative influences of this visualization on participants' cybersickness and liking, yielding a clear advantage of the discrete visualization in our results.

We suggest investigating additional visualization techniques as possible alternatives to strengthen participants' sense of orientation while maintaining the benefits of undo actions. For example, a motion blur in the style of superimposed teleport images could provide an intermediate between discrete and continuous visualization. Also, adding a visual indication of where one lands when undoing - similar to the position indication provided by the teleport beam - could help users orient themselves in the scene. As another way to increase users' orientation, we suggest investigating an alternative implementation of orientation undo: In our experiment, we reset the orientation based on the gaze direction (i.e., the orientation of the HMDs). This could adversely affect the user's orientation ability since only the perspective is restored, not the body pose. An alternative implementation based on the forward vector of the body could alleviate this concern. However, it would require additional tracking hardware or rely on heuristics based on the position of the controller and head position, which would inherently introduce some uncertainty. Further work is needed to conclude on the best design for undo actions.

7 CONCLUSION

In this paper, we explored the effect of undo actions as an extension to point&teleport on the participants' efficiency, orientation, and user experience. For this, we proposed eight variations of undo actions based on the availability of position and orientation undo and different movement visualizations. We compared the variations in a controlled experiment with 24 participants. We found promising results, indicating that undo action can provide users with an easy and fast option to skip travel times for returning to previously visited locations in VR. However, our results indicate that undo actions can negatively influence the participant's spatial orientation in the virtual scene, calling for further research in this direction.

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