You Have Arrived... Kind of: Investigating the Limits of Undetectable Destination Displacement During Teleportation

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Abstract

Teleportation has become a popular locomotion method for virtual reality due to lesser demands on physical space and decreased levels of motion sickness compared to other methods. However, prior work has shown that these advantages come at the cost of impaired spatial perception and awareness, the extent to which is still largely unknown. In this work, we present a within-subjects study ($N = 29$) that explores the effects of teleportation on spatial perception by investigating how much humans can be unknowingly displaced relative to their intended destination during teleportation. After teleporting to the specified location, participants indicated the direction and magnitude (small, medium, large) of the perceived shift or rotation. Displacement from the target happened either as a translation in the forward- or strafe-axis, or a rotation about the up-axis at the intended target. Each displacement condition included eleven offsets that were repeated six times. Our results indicate points of subjective equality, which show a significant perceptual shift along the forward-direction, as well as detection thresholds, which indicate a comparatively wide range in which humans are unable to detect induced shifts. Furthermore, our results show that even if humans are able to detect these shifts, larger ones can be introduced before their magnitudes are rated as medium or large, which provides ample opportunities for interface designers who want to leverage these results in virtual reality.

CCS Concepts

• **Human-centered computing → Virtual reality**; **Empirical studies in interaction design**.

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1 Introduction

Teleportation has become a particularly popular locomotion technique due to its reduced demands on physical space [7, 13, 33] and lower levels of motion sickness [13, 35, 59] compared to other locomotion methods. According to a recent survey on trends in virtual reality (VR) locomotion research by Martinez et al. [37], Point-and-Teleport [7] is the most explored selection-based technique and the most widely studied locomotion technique overall. Its popularity even extends to commercial applications, as seen in its 32.7% adoption rate among the 330 most used VR applications released between 2016 and 2023 [1].

Despite these advantages, prior work has shown that teleportation comes at the cost of impaired spatial perception and awareness [2, 6, 47], the extent to which has yet to be fully explored. Its discontinuous translation of the viewport distorts spatial awareness due to a lack of self-motion cues like optic flow [3, 15]. Given its widespread use, it is crucial to understand the degree to which spatial awareness is being affected.

This disruption in spatial updating caused by teleportation offers a unique opportunity to study the flexibility and limits of human spatial perception. Thus, we leverage teleportation to examine how sensitive perceptual systems are to discrepancies in spatial transformations when deprived of self-motion cues. This work investigates the perceptual boundaries of spatial awareness during teleportation by introducing subtle displacements and conducting a user study ($N = 29$) that evaluates how much a user can be offset from their intended destination without detection. We then quantify the range over which users can be unknowingly displaced and the ranges over which users classify displacements as “small”,“medium”, and “large”. We used the following research questions to guide our investigation:

RQ1 At what point can users reliably distinguish between the directions of a teleportation-induced displacement?

RQ2 To what extent can users be unknowingly displaced from their intended location during teleportation?

RQ3 At what magnitudes do users begin to categorize a displacement from their intended teleportation destination as "small", "medium", or "large"?

While spatial perception during teleportation remains underexplored, related work in redirected walking offers valuable insights. Redirected walking [48] decouples the user's physical and virtual movement by applying undetectable manipulations to the visual scene that cause the user to unknowingly reposition or reorient themselves within their physical space. Much of this work relies on psychophysical experiments to determine detection thresholds—the range of gains over which users are unable to reliably detect the difference between their physical and virtual movement [8, 53, 54].

Although redirected walking and teleportation differ in how they manipulate user movement, they share methodological parallels that allow users to traverse virtual environments (VEs) that are larger than their physical space by altering the user's virtual position without a direct correspondence to real world movement. Thus, we adopted a within-subjects psychophysical design based on an n-alternative forced-choice (nAFC) task to investigate spatial perception during teleportation since similar methodologies have been employed redirected walking literature. The nAFC task allowed us to determine the displacement magnitude at which users can distinguish between directions (point of subjective equality), the range over which users can be unknowingly displaced (detection thresholds), and the thresholds at which users classify displacement magnitudes as small, medium, or large (magnitude thresholds). During the study, participants experienced displacements after teleporting to the target location. These displacements occurred as either a translation in the strafe- or forward-direction, or as a rotation about the up-direction (see Figure 1). Each axis included eleven offset levels, including forward, backward, lateral, and rotational deviations from the intended teleport target pose.

Our findings reveal asymmetries in how users perceive forward translations and yaw rotations during teleportation. We identified detection thresholds for the displacements for each displacement type and established magnitude thresholds for categorizing displacements as small, medium, or large. Based on these results, we developed a set of design recommendations that offer practical guidance for designing VR teleportation systems that minimize perceptual disruptions.

2 Related Work

2.1 Spatial Perception and Teleportation

Teleportation was first introduced by Mine et al., whose implementation instantly transitioned the user's viewpoint to a selected destination through pointing [40]. Nearly two decades later, the widely adopted Point-and-Teleport [7] implementation was formalized, becoming a standard in modern VR applications and the most widely studied locomotion technique [37]. A major contributing factor to teleportation's dominance is its ability to reduce simulator sickness [16, 33, 59]. The discontinuity of teleportation disrupts optic flow, therefore reducing simulator sickness but also impairing spatial perception and awareness [3, 14, 38]. Interrupting optic flow also causes disruptions in visual continuity and self-motion cues, both of which are critical for spatial orientation and memory [52]. In addition to this decreased spatial perception, teleportation has been shown to increase cognitive load, especially when users are required to reorient themselves after each jump [9, 14]. When users arrive at a new location facing an unexpected direction, integrating the new view into their existing mental map becomes harder [14]. This leads to fragmented spatial representations and increased cognitive effort when navigating or recalling spatial layouts.

Although previous work has explored the relationship between teleportation and spatial perception, few studies have quantitatively assessed its impact. In order to design interfaces that mitigate the drawbacks of teleportation, it is essential to establish measurable insights into how teleportation impacts spatial perception. Many previous works that improve spatial perception during teleportation do so by providing more spatial representations of the environment prior to travel such as portals [21, 31, 57] and preview avatars [17, 26, 58]. As a result, post-travel techniques that support spatial perception have been underexplored. This work addresses that gap by investigating the limitations of spatial perception and awareness following teleportation, with the goal of informing future interface designs.

2.2 Estimating Perceptual Thresholds in Redirected Walking

Redirected walking [48] relies on applying undetectable visual manipulations that cause a user to unknowingly reposition or reorient themselves within their physical space, enabling exploration of a larger virtual space. Redirection can be achieved by introducing rotations and translations (controlled by *gains)* to the user's virtual movements as they move about the physical space [54]. This technique is most effective when these manipulations are imperceptible to the user, thus it is advised that gains do not exceed the detection threshold–the smallest gain magnitude that users can reliably perceive. A substantial amount of prior work in the redirected walking community has studied how detection thresholds vary based on different system configurations [23, 41, 61]. Many of these studies have used variations of the n-alternative forced-choice (nAFC) task to assess users' perception of induced manipulations [5, 8, 11, 32, 34, 54]. The nAFC task has become a widely-adopted method due to how its ability to isolate perceptual sensitivity from decision biases [30, 36]. Some studies have used a simplified version of the task that is based on staircase procedures [10, 25, 48]. However, these methods are less effective in eliminating bias compared to the full nAFC approach. Based on this, we chose to employ a full nAFC task procedure in our study.

3 Psychophysical Experiment

In this section, we describe the experiment we performed to analyze how sensitive humans are to subtle yaw rotations and forward/backward or leftward/rightward translations in VR at the time of teleportation. The experiment was approved by the institutional review board of our university.

(a) Teleport Origin Pose

(b) Teleport Target Pose

(c) Displacement Vectors

(d) Forward Translation Example

(e) Left Translation Example

(f) Left Yaw Rotation Example

Figure 1: Image sequence illustrating the teleportation displacements and resulting viewport changes observed in the user study: (a) participant selecting the teleport target, indicated by the circle, (b) view after teleportation without any displacement from the target pose, (c) vectors depicting the displacement axes along which the viewport may be offset relative to the teleport target, (d) example of a forward translation, (e) example of a left strafe translation, and (f) example of a left yaw rotation.

3.1 Participants

We recruited 33 participants from our university community, 29 of whom were included in the final analysis. The remaining 4 participants were excluded due to a misunderstanding of the task, as evidenced by their plotted responses. Their data lacked the expected curvature that would have indicated the detection of extreme values, hence failing our sanity checks. The included 29 (9 female, 20 male) participants were between the ages 19 and 45 ($M = 26.0, SD = 6.1$). All of the participants had normal or corrected-to-normal vision, 16 of whom wore glasses during the experiment. 1 participant reported color-blindness and 2 reported strong astigmatism. None of the participants reported any cognitive or motor impairments. All of the participants were right-hand dominant. VR experience among the participants varied with 6 having little experience, 8 having some experience, and 15 of them having high levels of experience. The participants were either students or non-student members of our university community who responded to open calls for participation, and received monetary compensation for their participation.

3.2 Material

3.2.1 Hardware and Software. Participants wore a Meta Quest 3 HMD, which provides a resolution of 2064×2208 pixels per eye with an approximately 122-degree diagonal field of view and a refresh rate of 90 Hz. Position and orientation tracking was done using the Quest 3's inside-out tracking system. A Quest Touch Plus[1] handheld controller served as the input device via which participants performed the teleportations and provided responses during the experiment. Participants were instructed to hold the controller in their dominant hand.

[1]https://www.meta.com/quest/accessories/quest-touch-plus-controller

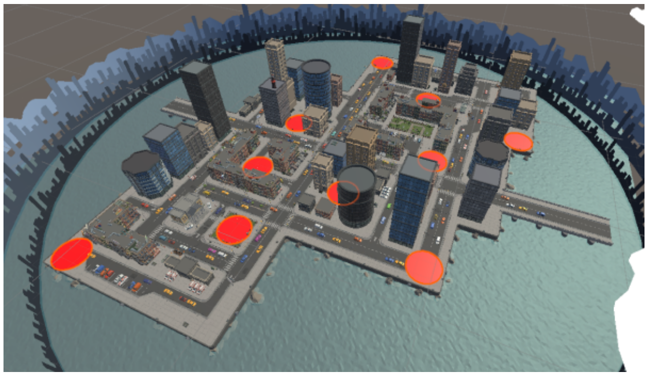


Figure 2: An aerial view of the virtual city environment highlighting the unique areas where teleportation targets were placed. Each area varied in the density and richness of visual cues provided by the surrounding city geometry to support the use of stimulus sampling. Locations provided at least ten meters of obstacle-free teleportation distance from the center of the red disk. Note that the red highlights are only included here for illustrative purposes and were not visible to participants during the trials.

The software was developed in Unity3D version 2022.3.36f1 as an Android package kit (APK) that was deployed and run on the HMD for untethered operation during the experiment.

3.2.2 Virtual Environment. The VE consisted of a large city environment acquired from POLYGON City - Low Poly 3D Art asset pack by Synty[2]. Our choice of a city environment was motivated by the literature in this field. For instance, Steinicke et al. [53, 54] decided on a virtual German city environment for their seminal redirected walking studies, and later studies by Bruder et al. [8, 11] used other city environments.

Ultimately, we wanted a scene that allowed users to explore multiple levels of stimuli to ensure that our work is generalizable. For the teleportation task, we identified ten unique places within the city environment that provided at least ten meters of obstacle-free space from the origin around the participant that was suitable for teleportation. The ten places within the environment were chosen with varying density and richness of orientation cues from the surrounding city geometry. See the red highlighted locations in Figure 2. Each trial in the experiment started from a randomly chosen location among these ten identified places. Participants were further oriented in a random direction within these places for each trial, while always facing the teleportation target.

To increase the ecological validity of results in this experiment, we leveraged stimulus sampling [60] with respect to the environment. Stimuli in the city environment include the floor geometry and texture, which ranges from plain asphalt to tiling patterns, sidewalks, and parking lines, as well as the density of objects in the surrounding area, from large buildings to cars, trash cans, mailboxes, and small flowers. Locations with a varying density level of objects were chosen to offset potential confounds introduced by landmark-rich areas.

[2]https://assetstore.unity.com/packages/3d/environments/urban/polygon-city-low-poly-3d-art-by-synty-95214

3.3 Method

3.3.1 Teleportation. The teleportation interface was implemented using the Meta XR All-in-One SDK version 76.0.1 [39]. Teleportation was initiated by pushing forward on the controller's joystick, at which point a curved arc would appear that would intersect the ground. While holding the joystick down, the participant could freely move the controller around to aim the arc. Once the joystick was released, instantaneous teleportation was initiated where the viewport was instantly transported to the new location. We decided on this curved arc as it is what Meta uses for their standard implementation of teleportation.

When pointing the arc at the designated teleport target and within a half meter, the end of the arc would snap to the center of the teleportation target. The target extended into a circle to visually indicate that the participant was able to teleport there. Participants were restricted to teleport only to the indicated target locations. This was also communicated by the ray being red when on an invalid location. We controlled these teleport target locations by only presenting one during each trial and randomizing their distance from the participant. To further use stimulus sampling, we decided to randomly present these teleport targets between five and eight meters away from the participant. This range was chosen due to the fact that off-the-shelf teleportation techniques such as the Meta XR All-in-One SDK [39] also limit the maximum distances for teleportation. At the time of teleportation a gain was applied and the teleportation target visual was removed to prevent participants from using it to asses the applied gain.

3.3.2 Study Design. For this experiment, we used a 3 (conditions) × 11 (offsets) × 6 (repetitions) experiment design. This resulted in 198 trials per participant, plus 7 training trials for each condition that were excluded from analysis.

We evaluated the following three conditions:

- Translation along the forward axis in teleportation direction (from the user's previous position to the target position) see Figure 1(d). We tested 11 translations $t \in \{0, \pm0.5, \pm1.0, \pm1.5, \pm2.0, \pm2.5\}$ (in m), each repeated six times. Negative values indicate a backward translation and positive values indicate a forward translation.
- Translation along the strafe axis relative to the teleportation direction see Figure 1(e). We tested 11 translations $t \in \{0, \pm0.5, \pm1.0, \pm1.5, \pm2.0, \pm2.5\}$ (in m), each repeated six times. Negative values indicate a leftward translation and positive values indicate a rightward translation.
- Yaw rotation around the up axis at the target position see Figure 1(f). We tested 11 rotations $r \in \{0, \pm7, \pm14, \pm21, \pm28, \pm35\}$ (in degrees), each repeated six times. Negative values indicate a counterclockwise rotation (leftward) and positive values indicate a clockwise rotation (rightward).

The three conditions were tested as blocks. The trials within each block and the order of the blocks were both randomized. Each block started with seven supervised training trials to ensure that participants understood the tasks. Short breaks were offered to participants between blocks. The distances, angles of rotation, and

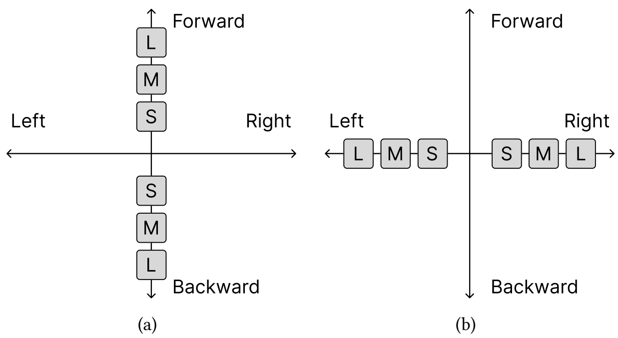


Figure 3: Response scale used for the six alternative choices: Participants indicated the perceived direction and magnitude (small, medium, large) that they were displaced during (a) forward/backward translations and (b) left/right translations or yaw responses ("left" here refers to counterclockwise rotations).

trial spot were randomized to prevent participants from becoming familiar with target locations, similar to [47, 53] study design.

This study design follows prior established protocols on psychometric evaluations of redirected walking detection thresholds (e.g., [8, 54]). The specific values we chose for our experiment were inspired by the parameters used in related work [5, 34, 62], as well as pilot testing.

3.4 Procedure

Pre-Procedure. Upon arrival, participants provided their informed consent, and were given an explanation of the experiment and instructions on how to perform the tasks. Prior to donning the HMD, participants completed the Simulator Sickness Questionnaire (SSQ) [29] (see Section 3.5.2) to assess their baseline health before the experiment.

Main Trials. After donning the HMD, participants were presented with task instructions via slides in the virtual scene and then completed three blocks with 7 supervised training trials. Each block consisted of 66 experimental trials (see Section 3.3.2). The order of the blocks and trials was randomized, and short breaks were offered in between blocks. In each trial, participants started in one of the ten predetermined trial origins within the city environment (see Section 3.2.1), which were chosen because they offered at least ten meters of obstacle-free space in any direction for teleportation. The heading of the participant within this space was randomized by using polar coordinates with a random angle. A single teleportation target (see Figure 1(a)) was presented directly in front of participants, who then aimed the controller in their dominant hand towards the teleportation target. Teleportation was initiated by pushing forward on the controller's joystick to cast the arc, then when the joystick was released participants would instantaneously arrive at the target location with one of the aforementioned offsets (see Section 3.3.2). Once the teleport was completed, a response scale was then presented in front of the participant, prompting them to judge the direction (left/right or forward/backward) and magnitude (small, medium, large) of the shift that they perceived relative to the teleport target (see Figure 3). Participants made their selection by simultaneously choosing a magnitude along the corresponding directional axis, thus indicating both aspects of their perception with a single response. A response on this scale could be chosen via straight-ray pointing selection by aiming the hand-held controller at one of the options and depressing the trigger. After the participant selected a response, the next trial started.

Post-Procedure. Once the three experiment blocks were completed, participants completed the SSQ once more to assess the before-and-after differences in their subjective health ratings, then they filled out the Igroup Presence Questionnaire (IPQ) [51], the short form of the User Experience Questionnaire (UEQ) [50], and a demographics questionnaire. The total time for the experiment per participant was approximately 45 minutes, they wore the HMD for approximately 30 minutes.

3.5 Experiment Task and Measures

3.5.1 n-Alternative Forced-Choice (nAFC) Task. To measure the amount of displacement that is unnoticeable during teleportation, we used a standard psychophysical procedure based on an n-alternative forced-choice task [22, 36]. This experimental method is an attractive and common procedure in the field of psychophysics as it eliminates many response biases and allows to isolate perceptual sensitivity from decision tendencies [30, 36]. Variants of this method have also been used extensively in the field of redirected walking [5, 8, 11, 32, 34, 54] to assess participants' perception of induced manipulations. While some work used a simplified version based on staircase procedures [10, 25, 48], these are unfortunately not as free from biases as the full method [24, 36]. Hence, we decided to perform a full nAFC task procedure using the method of constant stimuli. In the method of constant stimuli, the applied stimuli are not related from one trial to the next, but presented randomly and uniformly distributed.

In each trial, participants choose a binary response between one of two directions. In our case, these were "forward" or "backward" for translations along the forward axis, "left" or "right" for translations along the strafe axis, and "left" or "right" for yaw rotations around the up axis (referring to counterclockwise or clockwise rotations, respectively). See Section 3.3.2. Moreover, participants had to choose between one of three magnitudes of the perceived change (small, medium, large). In total, this resulted in $n = 2$ (directions) $\times$ 3 (magnitudes) answer possibilities in this nAFC task. These six answer possibilities were presented on a response scale that can be seen in Figure 3. Answers like "I don't know" are not allowed with this method, hence the omission of a "no offset" choice. Instead, participants have to choose one of the two general directions randomly and will be correct in 50% of the cases on average.

Expanding the number of possible responses is an attractive change to the nAFC task that provides additional insights into the perceived magnitude of the change in direction. This allows us to then assess the range of stimuli that are perceived for each magnitude, thus determining a magnitude threshold. This variation is also backwards compatible due to the capability of compressing the increased number of 6 responses into the traditional binary responses by only considering the chosen direction.

Psychometric Function. Once all responses for all stimuli had been collected, a psychometric function [30] was fitted to the data to describe the discrimination performance. The x-axes in these graphs indicate the stimulus levels. In line with the response scales that were shown to participants (see Figure 3), the y-axes on these graphs represent the two directions and the three magnitudes. Our results plots (see Figure 4 below) were generated with a y-value of 0 indicating chance level and uncertainty, y-values of ±1 indicating responses with a "small" magnitude, y-values of ±2 indicating responses with a "medium" magnitude, and y-values of ±3 indicating responses with a "large" magnitude.

Point of Subjective Equality (PSE). The stimulus at which the participants respond "left" (versus "right") or "forward" (versus "backward") in 50% of the trials is taken as the point of subjective equality at which participants estimate the position/orientation as accurate (i.e., no deviation from the intended teleportation target pose). As the stimulus level increases or decreases from this value, the ability of the participant to detect the difference increases.

Detection Thresholds (DTs). A detection threshold is the stimulus level at which participants can just detect the introduced change. Since the detection rate is often a smooth and gradually increasing function, in psychophysics, usually the point at which the function reaches the middle between the chance level (y-axis value of 0, see above) and the responses where participants were just able to detect the induced stimuli (y-axis values of ±1 for "small" responses, see above) is taken as a detection threshold [54]. Hence, the "upper" detection threshold is defined as the stimulus level at a y-axis value of 0.5, and the "lower" detection threshold is the one at -0.5.

Magnitude Thresholds (MTs). The response scales included three levels of magnitude (small, medium, large) that participants were asked to rate. Similar to the detection thresholds above, magnitude thresholds are defined as the midpoints between two magnitude levels. Specifically, the lower "medium" magnitude threshold is defined as the point with a y-axis value of -1.5 at the midpoint between small responses (-1) and medium responses (-2). Similarly, the lower "large" magnitude threshold is the point on the y-axis with -2.5 at the midpoint between medium responses (-2) and large responses (-3). Correspondingly, the upper "medium" magnitude threshold is defined at y-axis value 1.5, and the upper "large" magnitude threshold at y-axis value 2.5. While all of these stimuli are detectable by participants, these magnitude thresholds indicate ranges in which the stimuli are considered small, medium, or large, which is important for practitioners and interaction designers who aim to leverage these results for teleportation interfaces in real-world systems or applications.

3.5.2 Questionnaires. Participants filled out the following questionnaires after completing the main trials of the experiment.

Simulator Sickness. We administered the SSQ [29] both before and after participants completed the VR trials. Participants rated a total of 16 sickness symptoms on a 4-point scale including None, Slight, Moderate, and Severe. We measure simulator sickness based on the change in their symptoms, and analyzed the difference in the weighted total of their score [56].

User Experience. We employed the short version of the UEQ [50] to assess overall user experience of teleportation with translational or rotational offsets. Participants responded via eight bipolar adjective pairs on a 7-point semantic differential scale. Responses form three dimensions: Pragmatic Quality, Hedonic Quality, and Overall.

Presence. We used the the IPQ [51] to measure sense of presence while in the VE. Participants indicated the extent each statement applied to their experience on a 7-point scale ranging from -3 to 3. The questionnaire consists of the three subscales spatial presence, involvement, and experienced realism.

4 Results

Figure 4 shows the psychometric functions for the pooled responses fitted to the response scales over all participants for the three directions. We refer to Klein [30] for details on the generation and interpretation of psychometric functions. All three psychometric functions show a very good *Goodness of Fit*, computed as the *Mean Square Error (MSE)*, with $MSE = 0.0089$ for Figure 4(a), $MSE = 0.0068$ for Figure 4(b), and $MSE = 0.0017$ for Figure 4(c).

The x-axes show the introduced shifts (translations or rotations) during teleportation and the y-axes show participants' perceived magnitudes of these shifts. The black diamonds indicate the mean responses and the vertical bars indicate the standard errors. The dark green range from the lower detection threshold (-0.5) to the upper detection threshold (0.5) indicates the range in which the introduced shifts are undetectable. The outer light green range from the lower medium magnitude threshold (-1.5) to the upper medium magnitude threshold (1.5) indicates the range in which the introduced shifts are detectable but rated as "small" in magnitude. The outer orange range from the lower large magnitude threshold (-2.5) to the upper large magnitude threshold (2.5) indicates the range in which the introduced shifts are rated as "medium" in magnitude. Finally, the red range outside the lower and upper large magnitude thresholds indicates the range in which the introduced shifts are rated as "large" in magnitude.

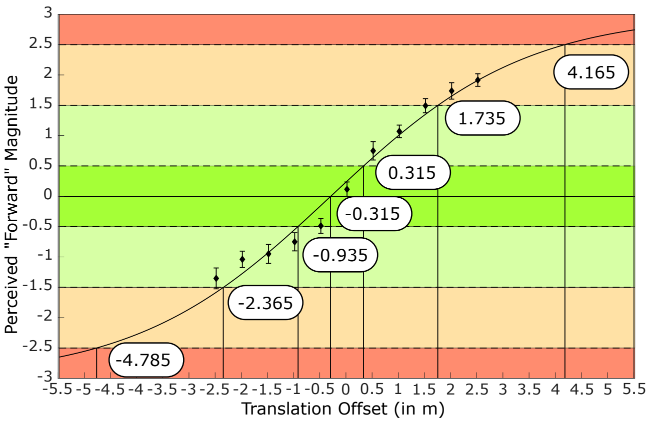
4.1 Points of Subjective Equality (PSEs)

The PSEs are the points where the psychometric functions show the midpoint between all response levels (y-axis value of 0), i.e., equal probability for indicating one of the two directions. See Figure 4.

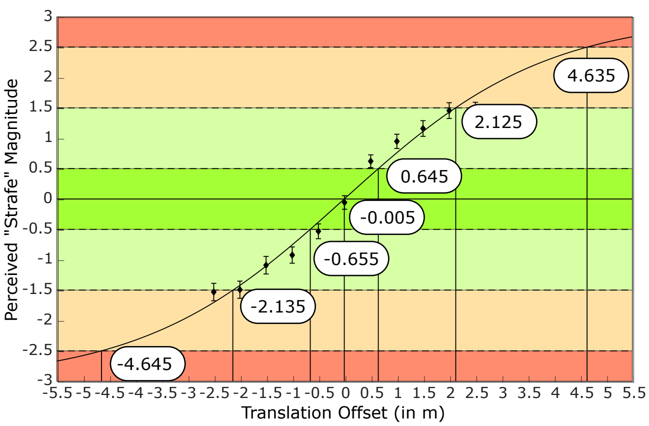
Our results for translations along the forward direction show an asymmetric pattern of the psychometric function, indicated by $PSE = -0.315$ meters. This means that a teleport that arrived 0.315 meters in front of the indicated target on the ground was perceived as more accurate than one that actually landed on the indicated target. Further, this asymmetry also extended to the ranges of the thresholds around the PSE.

We found no such asymmetry for translations along the strafe axis ($PSE = -0.005$ meters). In other words, participants perceived a teleport as most accurate that arrived centered (in terms of left and right translations) on the target.

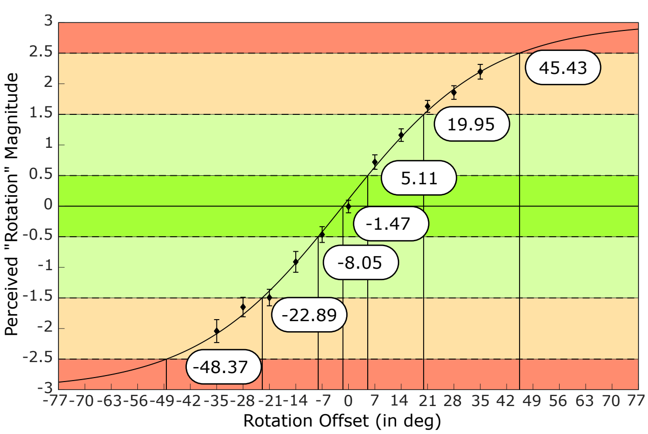
Lastly, we again found a slight asymmetry in the PSE for yaw rotations around the up-axis ($PSE = -1.47$ degrees). This means that a teleport that rotated the view by 1.47 degrees to the left (counterclockwise around the up-axis) was perceived as more accurate than one that kept the view oriented in the same direction as



(a) Translation Along Forward Axis



(b) Translation Along Strafe Axis



(c) Yaw Rotation Around Up Axis

Figure 4: Results showing the psychometric functions for (a) translations along the forward axis, (b) translations along the strafe axis, and (c) yaw rotations around the up axis. From left to right, the highlighted values indicate the thresholds: lower large magnitude, lower medium magnitude, lower detection threshold, PSE, upper detection threshold, upper medium magnitude, and upper large magnitude.

before the teleport. Again, this goes in line with an asymmetry in the ranges of the thresholds around the PSE.

4.2 Detection Thresholds (DTs)

The upper and lower detection thresholds for the three conditions are the points where the psychometric functions indicate the midpoint between the chance level (y-axis value of 0) and those responses indicating that participants were able to notice the stimuli (indicated "small" responses on the y-axis at ±1). See Figure 4.

For translations along the forward axis, we found a lower DT of -0.935 meters and an upper DT of 0.315 meters. It means that participants could not detect the introduced stimuli between a backward translation of 0.935 meters and a forward translation of 0.315 meters. In total, this indicates a range of 1.25 meters over which translations along the forward direction can be applied before participants are just able to detect the changes. In line with the asymmetry observed for the PSE, this range is also shifted backwards in space, meaning it is less detectable if the teleport terminates in front of the indicated teleport target.

For translations along the strafe axis, the DTs indicate a symmetric range from the lower DT at -0.655 meters to the upper DT at 0.645 meters. This means that translations from 0.655 meters to the left to 0.645 meters to the right (total range of 1.3 meters) can be applied before participants are just able to detect them.

Last but not least, for yaw rotations around the upaxis, we again found a slight asymmetry with a lower DT at -8.05 degrees and an upper DT at 5.11 degrees. This indicates a range from a leftward (counterclockwise) rotation of 8.05 degrees to a rightward (clockwise) rotation of 5.11 degrees. It means that stronger yaw rotation can be applied to the left than to the right. In total, this indicates a range of 13.16 degrees in which yaw rotations can be induced before participants are able to just notice the stimuli.

4.3 Magnitude Thresholds (MTs)

The upper and lower magnitude thresholds for the three conditions are the points where the psychometric functions indicate the midpoints between the indicated magnitudes (y-axis values of ±1.5 and ±2.5). See Figure 4.

For translations along the forward axis, we also found an asymmetry in the magnitude thresholds. The thresholds indicate that backward translations of more than 4.785 meters are perceived as large, those between 2.365 and 4.785 meters are perceived as medium, and those between 0.935 and 2.365 meters are perceived as small. For forward translations, those of more than 4.165 meters are perceived as large, those between 1.735 and 4.165 meters are perceived as medium, and those between 0.315 and 1.735 meters are perceived as small.

For translations along the strafe direction, we found no asymmetric tendencies. The thresholds indicate that leftward translations of more than 4.645 meters are perceived as large, those between 2.135 and 4.645 meters are perceived as medium, and those between 0.655 and 2.135 meters are perceived as small. For rightward translations, those of more than 4.635 meters are perceived as large, those between 2.125 and 4.635 meters are perceived as medium, and those between 0.645 and 2.125 meters are perceived as small.

For yaw rotations about the up axis, we again found a slight asymmetry. The thresholds indicate that leftward rotations of more than 48.37 degrees are perceived as large, those between 22.89 and 48.37 degrees are perceived as medium, and those between 8.05 and 22.89 degrees are perceived as small. For rightward rotations, those of more than 45.43 degrees are perceived as large, those between 19.95 and 45.43 degrees are perceived as medium, and those between 5.11 and 19.95 degrees are perceived as small.

4.4 Questionnaires

The total SSQ [29] scores showed a significant (though minor) increase with a Wilcoxon Signed Rank test and Bonferroni correction from before the experiment (M = 6.45, SD = 10.43) to after the experiment (M = 9.67, SD = 9.97), z = -2.68, p = 0.007, in line with what we expect after 30 minutes of wearing an HMD and performing a task.

The UEQ [50] scores indicate that participants judged teleportation with translational and rotational offsets as "Good" (M = 1.72, SD = 0.97) in terms of its *pragmatic quality*, as "Above Average" (M = 1.17, SD = 1.05) for its *hedonic quality*, and as "Good" (M = 1.45, SD = 0.80) for *overall user experience.*

The IPQ [51] scores indicate a reasonably high *spatial presence* (M = 1.98, SD = 0.71), *involvement* (M = 1.42, SD = 0.67), and *experienced realism* (M = 0.99, SD = 0.58) despite the translational and rotational offsets that were applied during teleportation.

5 Discussion

This study investigated human sensitivity to translations and rotations during teleportation. Our findings provide several important insights into how users perceive teleportation, the thresholds at which users become just aware of displacements from the target pose, and their overall estimation of the magnitudes of introduced translations and rotations.

5.1 Asymmetry in the perception of translations and rotations during teleportation

Regarding **RQ1**, our results reveal an asymmetry in human perception during forward translations and yaw rotations. Previous work by Steinicke et al. [53, 54] and Bruder et al. [8, 11] also saw an asymmetric pattern in their translation gains and rotation gains PSE values. Thus, it was unsurprising to see a similar asymmetry of PSE values for both our forward-axis translations and yaw rotations, as this is consistent with prior findings. Meanwhile, translations along the strafe axis had no such asymmetry in their psychometric function as see in the PSE of -0.005 meters, revealing that participants were able to detect a displacement and perceived the teleport as most "accurate" when no displacement occurred. We believe that these lateral translations were more noticeable due to the human visual system's increased sensitivity to motion cues in the peripheral visual field [44], thus positional changes of surrounding landmarks were more pronounced.

During translations along the forward-axis, participants consistently underestimated the distance to their target destination and perceived that they were arriving 0.315 meters behind the target during translations along the forward-axis, indicated by the PSE value of -0.315. This asymmetry and lower sensitivity to forward-axis translations may be attributed to the consistency of the environmental reference frame. Although the distance between the user and the landmark in from of them changes during teleportation, the user's heading and perspective remain constant thus maintaining the overall spatial configuration. Distance estimations in VEs are only 75% of the actual distance [27, 28], thus a 0.315 m offset could fall within the margin of perceptual inaccuracy. These results indicate a potential connection to distance underestimation in VR and other spatial misperception effects [19, 49] which warrant further evaluation.

Furthermore, our results indicate that a slight rotation of 1.47 degrees to the left (counterclockwise) is perceived as "accurate" during yaw rotations about the up axis. Based on anecdotal feedback, we believe that this may be a result experimental noise introduced by the entirely right-handed participant sample we tested in this study. As participants were indicating the teleportation with the curved ray using the controller in their dominant hand at an offset to the right side of the torso, they thus aimed the ray from their right side at the target, which produced a slightly off-center ray. With the ray terminating at the target at and angle, it seems likely that this slight angle led participants to perceive this slight shift as more accurate than a straight-out translation. However, this potential interpretation should be validated in future work, e.g., by recruiting specifically left-handed participants.

5.2 Wide range of undetectable translations and rotations during teleportation

Regarding **RQ2**, our results exhibit a wide range in which users can be displaced from the target during teleportation before they start to notice. Our results show that participants could not detect translations over a 1.25 meter range along the forward axis or a 1.3 meter range along the strafe axis. They also could not detect yaw rotations over a 13.16 degree range about the up axis. The aforementioned asymmetry also extended to the detection thresholds, indicating that participants were more susceptible to translations in forward direction and yaw rotations in counterclockwise direction.

It should be noted that these are conservative thresholds of human sensitivity to such induced translations and rotations. One advantage of the expanded 6AFC task that we employed is its backwards compatibility with the traditional 2AFC task by considering only the chosen direction. We compared detection ranges derived from both variation and found that the 6AFC task yielded consistently smaller detection ranges than the 2AFC task for each of the selected transformations. For example, along the forward axis, the 6AFC task produced a detection range of 1.25 meters ($[-0.935, 0.315]$), while the 2AFC task produced a detection range of 2.23 meters ($[1.295, 0.935]$). This suggests that expanding the number of response options may enhance sensitivity in spatial displacement detection.

Furthermore, participants in this study were aware of the possible displacements and were looking out for them. It is very likely that even larger displacements would go unnoticed if the users are distracted or not looking out for these manipulations. For instance, prior work in the context of redirected walking has shown that the use of distractors can increase the range of applicable manipulations before they become noticeable [45, 46]

5.3 Broader range of detectable translations and rotations with low magnitude ratings

Regarding **RQ3**, by providing response options for perceived magnitude in each direction, we were able to determine a range of magnitude thresholds for perceived "small," "medium," and "large" displacements from the target. Continuing the asymmetric patterns mentioned above, the magnitude thresholds also showed an asymmetry for translations along the forward axis and yaw rotations about the up axis.

Most of the range of displacements we tested in this study, despite being comparatively wide compared to related work, was rated by participants as "small" or "medium"—with barely any rated as "large," despite the largest translation offset being 2.5 meters and the largest rotation offset being 35 degrees. Since these judgments are subjective, it could be argued that these ranges are suitable for practical applications because if users do not rate them as "large" it stands to reason that they would not rate them as "too large" either. However, this aspect should be evaluated in future work.

Overall, the magnitude thresholds provide interaction designers with a range of attractive options during the development of a VR system or application. As a guideline for interaction designers, we recommend either relying on the detection thresholds if it is imperative to include subtle displacements that are unnoticeable, or alternatively using a broader range of displacements that users may detect if they pay attention but would still regard as "small" or "medium." These may in particular be interesting in situations where the added benefit of being able to control teleport displacements outweighs the potential drawbacks of using detectable manipulations, such as to control unintended positional drift [12, 43].

5.4 Design Recommendations

In addition to the insights on the effects of teleportation on spatial perception, our results offer broader implications for implementing teleportation in general. Below, we outline key design recommendations for interface designers seeking to leverage these findings.

The PSE values indicate the displacement at which participants can reliably distinguish their direction of movement. Notably, our results found that a -0.315 meter offset along the forward axis was perceived as the most "accurate". This suggests that users find a backward displacement more natural. Thus, teleportation should place users 0.315 meters behind their intended destination to facilitate a more intuitive experience that better aligns with perceptual expectations.

Our identified detection and magnitude thresholds provide a framework for managing suboptimal user-selected teleportation target that conflict with narrative or environmental expectations. These thresholds can be used to subtly reposition users to a more plausible location without them noticing, thus preserving narrative coherence and immersion.

5.5 Limitations

While our study provides valuable insights into spatial perception during teleportation, a few limitations should be noted. Specifically, our study only looked at translations along the ground plane (along the forward- and strafe-axes) and yaw rotations (around the up-axis). We did not analyze human sensitivity to translations in the up-axis during teleportation, which may be interesting to study in the emerging field of teleportation to mid-air targets [57]. Further, we did not include conditions to analyze pitch and roll rotations during teleportation. Although the practical purposes of such offsets may be unclear, with a few potential exceptions [4], these results may shed light on additional elements of embodied cognition with respect to the axes of human spatial perception during visual disruptions [18]. These factors may be investigated in future work.

In order to better understand the extent to which spatial awareness was being affected, we were also interested in the magnitude of perceived displacement from the intended teleportation target. The 2AFC task is typically employed during psychophysical experiments that investigate the perceived direction of displacement. Since our study is interested in both the perceived direction of displacement and its magnitude, we used an expanded 6AFC format that enabled participants to rate the magnitude and direction of displacement in a single response. This approach allowed us to identify perceptual thresholds corresponding to "small", "medium", and "large" magnitudes. However, future work should validate these magnitude thresholds using more established magnitude estimation methods such as Stevens' Magnitude Estimation [55] and visual analogue scales (VAS) [20].

6 Conclusion

In this paper, we presented a user study in which we investigated human sensitivity to induced translations and rotations during teleportation in VR. Our results show an asymmetry in human perception of forward translations and yaw rotations during teleportation, which has wider implications for teleportation techniques in VR in general. Further, we identified detection thresholds that indicate a range of stimuli over which VR users are not consciously able to notice the induced translations and rotations. Last but not least, we also identified magnitude thresholds that indicate further ranges of stimuli that are detectable by users but are judged at different magnitudes, from small to medium and large. These are highly relevant for interaction designers in VR, thus we provide design recommendations based on our findings. These findings can be leveraged for user interfaces as an orthogonal supplement for other redirected walking techniques [42, 54] or as a means to reduce unintended positional drift [12, 43]. Future work may extend the range of factors that were studied in this paper, and explore practical controllers, systems, and applications leveraging these techniques and results.

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