Published: 12 November 2025

Citation in BibTeX format

VRST '25: 31st ACM Symposium on Virtual Reality Software and Technology
November 12 - 14, 2025
QC, Montreal, Canada

Conference Sponsors:
SIGCHI
SIGGRAPH

RESEARCH-ARTICLE

Reimagining Go-Go: Effects of Signifiers in VR Selection Techniques

NICHOLAS JENNINGS, University of California, Berkeley, Berkeley, CA, United States

ANDRII MATVIIENKO, KTH Royal Institute of Technology, Stockholm, Stockholms, Sweden

Open Access Support provided by:

KTH Royal Institute of Technology

University of California, Berkeley

Reimagining Go-Go: Effects of Signifiers in VR Selection Techniques

Nicholas Jennings
University of California, Berkeley
Berkeley, California, USA
nicholasjennings@berkeley.edu

Andrii Matviienko
KTH Royal Institute of Technology
Stockholm, Sweden
andriim@kth.se

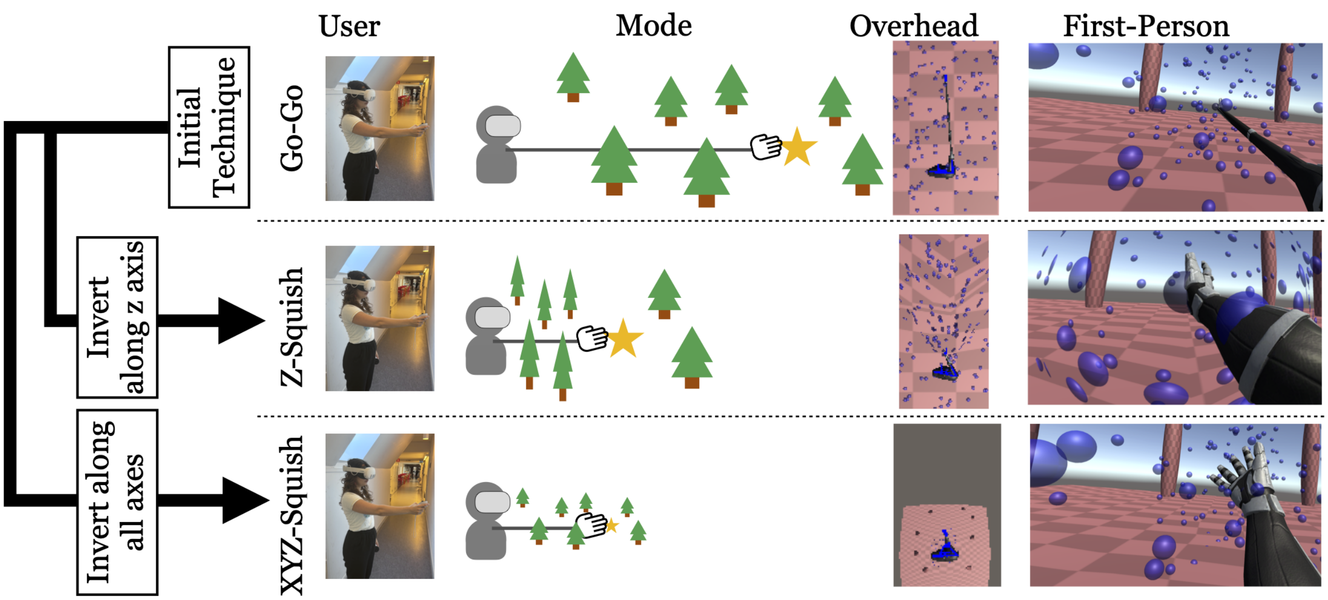


Figure 1: Overview of the three selection techniques. Identical user interactions cause the virtual cursor to move to the same point in the virtual world; however, the visual signifiers of this movement are different for each interaction.

Abstract

Interaction techniques for room-scale Virtual Reality (VR) are commonly presented wholesale; however, decoupling the mechanics and signifiers of these interactions offers new interaction possibilities. To explore the effect of signifiers on VR interactions, we created two new interaction techniques (forward-axis compression and multi-axis compression) with identical mechanical mappings to the existing Go-Go technique but with different signifiers. We conducted usability and illusory detection studies (N=18) to compare the interactions. Our results indicate that participants had comparable performance regarding target selection time and the number of missclicks with standard *Go-Go* and forward-axis compression for both small and large spheres. Additionally, multi-axis compression causes Go-Go to become illusory at low-distance multipliers. We propose that separating mechanics from signifiers is beneficial for creating new VR interactions.

VRST '25, Montreal, QC, Canada

ACM ISBN 979-8-4007-2118-2/25/11
https://doi.org/10.1145/3756884.3766014

CCS Concepts

• **Human-centered computing** → **Virtual reality**; **Interaction techniques**; *Usability testing*.

Keywords

virtual reality, signifiers, amplified movement

ACM Reference Format:
Nicholas Jennings and Andrii Matviienko. 2025. Reimagining Go-Go: Effects of Signifiers in VR Selection Techniques. In *31st ACM Symposium on Virtual Reality Software and Technology (VRST '25), November 12–14, 2025, Montreal, QC, Canada.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3756884.3766014

1 Introduction

Virtual environments accommodate limitless spaces for interaction and exploration while having users in limited physical spaces. These infinite virtual spaces can be explored, for instance, via amplified movements, allowing users to cover larger virtual spaces by accelerating their virtual movement or amplifying the mapping of physical ones [15, 28, 30, 34]. These interaction techniques can be conceptually decomposed into **Remappings**, the underlying change in how a user's movement/pose in physical space is altered in virtual space; and **Signifiers**, the visual changes that communicate the remapping to users[1] [2]. One way to classify these signifiers is to determine which part of the virtual environment changes to visualize the remapping. Egocentric signifiers modify the virtual avatar, Exocentric signifiers modify the virtual world, and Invisible signifiers do not visualize the remapping. Since many remappings are only concerned with the relative position of the virtual body and world, many egocentric and exocentric signifiers can be interchanged while maintaining the remapping. Practically, this means replacing signifiers that stretch or extend the virtual body with ones that "squish" or shrink the world. Such a substitution provides a new dimension for VR designers to explore nearly every time a beyond-real remapping is used in an interaction technique (except when the signifier serves a particular purpose, e.g., as a narrative element in a video game). However, since the isolated effect of signifiers on interaction technique usability performance has not been explored, it is unclear if this dimension is fruitful to investigate.

While the primary function of a signifier is to inform the user of the remapping and give the user feedback (to use it properly), these visual changes also impact the performance of the interaction technique. Existing interaction techniques with similar remappings but different signifiers (such as Ninja Hands [26] and OVRlap [27]) show that signifiers are not necessarily tied to remappings; however, their independent effect on performance and user reception has yet to be fully explored. Therefore, we explore the role VR signifiers play in overcoming limited physical spaces while interacting in virtual spaces and to what extent they facilitate this interaction. We expect that modifying the signifier of a remapping interaction can produce positive effects on performance separate from the mechanical effects of the remapping.

In this paper, we propose two new interaction techniques by modifying the signifiers of a popular existing technique, while leaving the remapping unchanged. Specifically, we modify the arm-stretching signifier of the *Go-Go* [25] technique (whose remapping applies a distance multiplier to the user's reach) to create two variant interaction techniques with signifiers that compress the virtual world along a single axis (the Z-Squish technique) and along multiple axes (the XYZ-Squish technique). We suspect that these visual changes should affect the performance of the interaction techniques, and the technique's *Illusory Threshold* defined as the point below which sensory systems produce illusions, i.e., the intensity above which the remapping becomes noticeable to users. Techniques with a large illusory threshold could be used as illusory interactions, which can be useful when realism is important to the application. Our results indicate that participants had comparable performance regarding target selection time and missclicks with *Go-Go* and Z-Squish, with XYZ-Squish performing worse in both metrics. Moreover, while there is a difference in a target selection time for *Go-Go* for different sphere sizes and distances (larger, closer spheres are selected faster), there is no such difference for Z-Squish, which indicates that target size and distance do not play a big role for Z-Squish. XYZ-Squish performed worse than standard Go-Go, but while Go-Go is always noticeable to users, the XYZ-Squish signifier is illusory at up to a 4.85 scalar multiplier. We propose that separating mechanics from signifiers could be a useful technique for researchers and designers creating new VR interactions.

In summary, our research contribution includes:

- Design and development of two interaction techniques based on forward- and multi-axis compression with identical mechanical mappings but different signifiers compared to established the *Go-Go* technique.
- An empirical evaluation of how viewing signifiers and mechanical mappings as independent can be used to explore VR interaction techniques.

[1]In relation to selection interactions, 'signifier' sometime refers specifically to indicators of whether an element can be selected [18]. In this paper we use the term more broadly to mean visual indicators that communicate the effects of the technique.

2 Related Work

2.1 Illusory Interaction

Motion-based VR illusions are consequences of a subtle mismatch between the sensory virtual and the real-world feedback [11]. To resolve this mismatch, it is essential to facilitate consistency of the sensory feedback with users' expectations governed by the predictions of their internal mental models. For example, the slightly extended length of the user's arm or hand in VR is an illusion that users will not notice, especially when focused on the primary task of, for example, selection, which we explore within this paper. Specifically for hands, researchers have explored illusions to redirect the users' hands when following surfaces [1, 16, 36] to provide an improved perceived haptic sensation. The mismatch between the visual and proprioceptive feedback in such illusions is typically resolved via visual dominance [13]. When studying VR illusions, researchers identify users' perceptual thresholds to ensure that the illusion remains unnoticed [1, 29], which we explore in the illusory experiment of this paper for Go-Go and XYZ-Squish thresholds. Illusory interactions can be used to retarget physical hand movements [10], which in turn can be used to reuse physical haptic props [3, 9]. Although these illusory interactions are essential to enhance the perception of realistic VR environments, previous research has shown that our cognitive system can adapt to repeated exposure to contradictory stimuli [4], which creates opportunities to explore open-ended forms of novel techniques focused on signifiers.

2.2 Ego- and Exocentric Signifiers

Homuncular Flexibility refers to the ability of humans to quickly adapt to control new body morphologies [32, 33]. This ability has practical applications in VR, as it allows interaction techniques that remap human movements to morphologies better suited to a given task. If these remappings go unnoticed by the user, the interaction is called Illusory; if the remappings are noticeable, the interaction is called Beyond-Real. In a review of beyond-real interactions, Abtahi et al. use the type of signifier (egocentric, exocentric, or invisible) to help categorize interactions [2]. Egocentric signifiers visualize interactions as modifying the virtual avatar's body. Examples include Go-Go, which increases user reach by extending their arm past a given threshold [25], and MultiSoma, a system that allows users to control up to 4 virtual bodies at once [21]. McIntosh et al. show that iteratively adapting avatar proportions can significantly improve performance on tasks [19]. Exocentric signifiers visualize interactions by modifying the virtual environment. Examples include

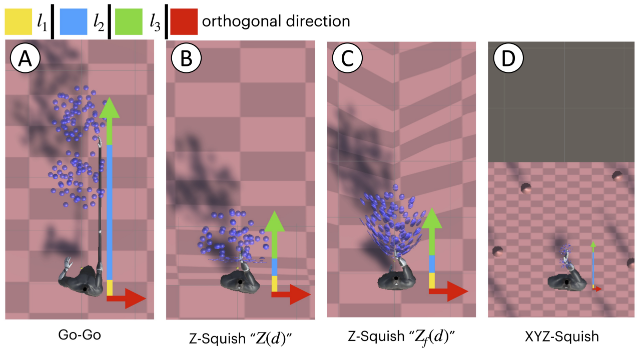


Figure 2: Selection techniques from overhead orthogonal perspectives: (A) Baseline Go-Go, (B) Z-Squish without the Z_f mapping, (C) Z-Squish, and (D) XYZ-Squish.

vMirror, which adds mirrors to the environment, allowing users to see and select occluded targets [17], and Poros, which brings selected portions of the world in reach of the user [24]. Wall-based Space Manipulation can be used to more arbitrarily manipulate spaces to allow for accurate manipulation of distant objects [5]. Mine et al. provide several examples of how manipulating the virtual world can help with selection, manipulation, and movement tasks [20]. Moreover, Di Luca et al. created a large-scale database of VR locomotion systems with a more granular categorization system than ego/exocentric signifiers [8]. Signifier-related categories include "Speed", "Nausea", and "Embodiment". Interactions that involve uniform scaling, such as World-in-Miniature [7] and I'm a Giant [35], can be seen either as an egocentric or exocentric interaction depending on how they are described. Nair et. al. use homuncular flexibility to create privacy tools for VR telepresence applications [22]. In this case, the visual signifier of the technique (particularly as other users perceive it) is more important than its mechanical effects. Interactions without any perceivable signifiers are said to be invisible. An example is Seven League Boots, which increases movement speed along a desired axis but has visual cues once the user starts moving [14]. Sometimes, an interaction will be unnoticeable to users and, therefore, illusory when a scalar in the remapping function remains in a given range. Steinicke et. al. provide a framework for determining this detection threshold [29]. Although these works have explored different types of signifiers, we still lack an understanding of their influence on users' interaction in VR, focused on object selection. In the following section, we describe the two techniques we designed and implemented based on egocentric and exo-centric, signifiers.

3 Techniques

To demonstrate how altering the signifier of interaction can lead to novel results, we apply the method to a classic beyond-real interaction: Go-Go [25]. We arrive at new techniques by converting the signifier of the base interaction to an exocentric signifier. In the following sections, we describe the base interactions and introduce the new techniques (Figure 2).

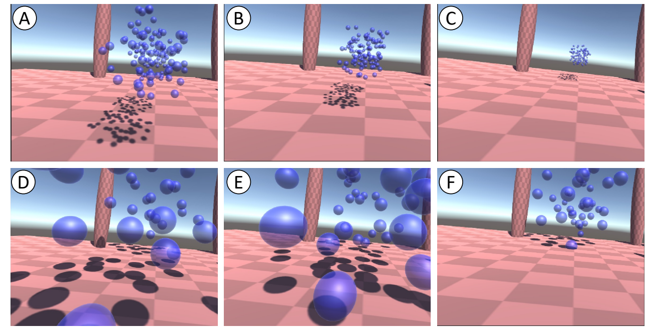


Figure 3: First person perspective on the selection task: small spheres selection (upper row) at distances of 3 (A), 4 (B), and 8 (C) meters, and large spheres selection (lower row) at distances of 3 (D), 4 (E), and 8 (F) meters.

3.1 Baseline Go-Go

In the Go-Go interaction technique, the user avatar's hands match the position of their physical hands within a specified horizontal radius. Once the user's hands extend further than the constant radius, the distance from the avatar's hand to the camera is increased quadratically with the extra distance. The formula for the avatar hand distance $G(h)$ given an initial hand distance h is:

$$G(h) = min(h, C) + S * max(0, h - C)^2 \tag{1}$$

where, C is a constant radius around the user, and S is a constant scale amount. For the selection task of our study, these values were set to $C = 0.3$ and $S = 170$.

3.2 XYZ-Squish

The XYZ-Squish technique inverts the Go-Go technique by compressing the world along all axes, instead of modifying the avatar. A vertex shader applied to each material in the scene calculates the distance from each point in the world to the avatar's head. The inverse of the Go-Go function is applied, and the vertices are redrawn at the resulting distances. This has the effect of "shrinking" the virtual world towards the avatar's head, such that the world point aligned with the avatar's hand in the Go-Go technique and is still aligned with the hand. The full equation applied to each vertex is:

$$X(d) = d * \frac{h}{G(h)} \tag{2}$$

where h is the same as in the Go-Go equation, G is the Go-Go equation, and d is the distance from a world vertex point to the camera. Notably, $\forall h \in \mathbb{R}, X(G(h)) = h$, so the position of the go-go cursor aligns with the avatar's unmodified hand. This allows the avatar to remain unmodified by the signifier, making it purely exocentric. Since all vertices are moved towards the virtual camera uniformly, the main visual signifiers of the interaction are eye parallax and the relative size of the avatar's body. Since the shrinking effect does not impact the avatar arm, it appears large relative to the world. The XYZ-Squish interaction can also be thought of as a modification of the World-in-Miniature [7, 31] interaction, where the world size is automatically tied to hand extension, and the center of world expansion is pre-determined.

3.3 Z-Squish

Since the Go-Go interaction is defined on the user's hand/cursor, any global vertex shader that inverts the Go-Go function at that point (that is, brings the Go-Go cursor position to the avatar's hand) is a valid exocentric signifier. Like XYZ-Squish, the Z-Squish interaction inverts the Go-Go technique as a world transformation. However, where the XYZ-Squish interaction shrinks the world uniformly, Z-Squish only shrinks the world along the forward direction the Go-Go hand extends down, i.e., the Z axis in local space. Z-Squish also avoids shrinking objects further from the avatar than the cursor hand. The full equation is:

$$\begin{aligned} l_1 &= min(p, C) \\ l_2 &= max(0, min(p, G(h)) - l_1) \\ l_3 &= max(0, p - l_1 - l_2) \\ Z(d) &= l_1 + (\frac{l_2}{S * max(0, h - C)}) + l_3 \end{aligned} \tag{3}$$

Where C, h, and S are as in the Go-Go equation, G is the Go-Go equation, and $p(d)$ (written in the equations as p) is the length of the camera-to-vertex vector projected onto the camera-to-hand vector. l_1 is the distance along p within the constant radius, l_2 is the distance between the constant radius and the cursor, and l_3 is the distance beyond the cursor (See Figure 2). At the world point where the Go-Go hand would land, $p = G(h)$, so $Z(G(h)) = h$.

Z-Squish also has an optional extra mapping, which only applies the Z-Squish function to vertices that are radially close to the Z direction, which takes the form of the following equation:

$$Z_f(d) = lerp(d, Z(d), (norm(\vec{d}) * norm(\vec{h}))^P) \tag{4}$$

$lerp(a, b, t)$ linearly interpolates between points a and b by $t \in [0, 1]$, $norm(\vec{d})$ is the normalized camera-to-vertex vector, and $norm(\vec{h})$ is the normalized camera-to-hand vector. Pilot studies indicated the Z_f mapping was more intuitive than the Z mapping, thus, Z-Squish refers to the Z_f mapping unless otherwise specified. Overall, while the XYZ-Squish interaction attempts to invert Go-Go using as simple an equation as possible, Z-Squish attempts to invert Go-Go while altering as little of the scene as possible.

4 Usability study

In this study, we explored the effect of signifier changes on each interaction type by comparing the performance of the baseline Go-Go, XYZ-Squish, and Z-Squish, on a selection task.

4.1 Participants

We recruited 18 participants (9 F, 9 M) aged between 19 and 38 ($M = 27.1, SD = 5.7$) using campus mailing lists and street recruitment. Three had never used VR before, ten had used VR a few times before, four had used VR many times, and one used VR regularly.

4.2 Study Design and Task

The selection task was designed to be within-subject with three independent variables: (1) *technique*, (2) *sphere cloud size*, and (3) *sphere cloud distance*. The technique has three levels : (1) Go-Go, (2) Z-Squish, and (3) XYZ-Squish. The sphere cloud size has two levels: (1) small spheres (10cm spheres in a volume formed by 120cm spheres) and large spheres (60cm spheres in a volume formed by 5m spheres). The sphere cloud distance has three levels and covers distances of 3, 4, and 8 meters. Sphere size and distance were tested in the same order for each participant. Small spheres were tested first at the 3m, 4m, then 8m distances, then large spheres in the same distance order. Technique order varied between participants. Since there were three techniques, there were six possible technique orders for the study. These orders were counterbalanced using a Balanced Latin Square.

To assess the Go-Go family of interactions, we modified the 3D sphere selection task by Zhang et al. [35]. For this, we populated selection spheres in a volume formed by two spheres in series away from the participant (Figure 3). The furthest nine spheres are marked as target spheres, and one target sphere is marked in yellow. Participants moved their selection cursor to overlap with a sphere to select a sphere and pressed the trigger button on their controller. The selection cursor was a sphere that matched the position and size of the rendered virtual hand[2]. Selecting the wrong sphere provides feedback by flashing the sphere red and vibrating the user's controller. When the participant selects the yellow sphere, another target sphere is marked yellow, and the process repeats until the participant has selected each of the nine target spheres. The selection task involves six sphere clouds at three starting distances (3m, 4m, 8m) and two sizes.The participants' task was to balance speed and accuracy. We measured (1) the time between each successful target selection and (2) the number of erroneous clicks. Unlike Zhang et al. [35], we randomized the sphere placement in every cloud. This prevented participants from learning the correct arm movements to select each target independently of visual input, since each selection technique only differs visually.

4.3 Apparatus and Procedure

We created the environments for both this study and the Illusory Threshold study (see Section 5), using the Unity game engine and deployed them on a Meta Quest 3 headset tethered to a desktop computer. Participants sat in a chair for all selection interaction tasks. Before each study, participants were given brief instructions on using the headset and were allowed to practice with the interaction techniques. The scenes used for these practice sessions were visually similar to those used for the study, but did not include the specific target elements of the usability task. For the Usability Study, participants were told to balance speed and accuracy when completing each task, and were allowed to rest between tasks to avoid fatigue. After each technique participants were asked a series of 7-point likert scale questions, which (along with some broader questions) included relevant questions from the Standardized Embodiment Questionnaire [23] and the NASA TLX.

4.4 Data analysis

To analyze the quantitative data, we fitted (generalized) linear mixed-effects models estimated using REML and nloptwrap optimizer using the `lme4` r package [6]. We included technique, tool, size, and their interaction as predictor variables and random intercepts for the participants. We employed Type III Wald chi-square

[2]Notably, due to the scaling nature of XYZ-Squish, it appeared relatively smaller than the rendered hand for that interaction as the hand extended.

Table 1: Table of results for the Selection Techniques. To prevent user fatigue, participants were allowed to skip a task if they spent more than 2 minutes on it without success. The number of participants who skipped (out of 18) is included in each task. In the one task where all users skipped, no data could be recorded.

	GoGo	XYZSquish	ZSquish
Small Spheres, 3m	Time: μ=3.393 σ=1.056 Clicks: μ=0.302 σ=0.316 Skips: 0/18	Time: μ=11.332 σ=3.837 Clicks: μ=4.167 σ=2.455 Skips: 10/18	Time: μ=4.914 σ=2.538 Clicks: μ=0.466 σ=0.863 Skips: 0/18
Small Spheres, 4m	Time: μ=3.688 σ=1.196 Clicks: μ=0.340 σ=0.295 Skips: 0/18	Time: μ=9.049 σ=4.154 Clicks: μ=5.175 σ=4.997 Skips: 11/18	Time: μ=3.998 σ=1.720 Clicks: μ=0.321 σ=0.212 Skips: 0/18
Small Spheres, 8m	Time: μ=8.193 σ=5.202 Clicks: μ=1.068 σ=1.324 Skips: 1/18	Time: Undefined Clicks: Undefined Skips: 18/18	Time: μ=4.968 σ=1.331 Clicks: μ=0.463 σ=0.445 Skips: 0/18
Large Spheres, 3m	Time: μ=2.314 σ=0.417 Clicks: μ=0.019 σ=0.041 Skips: 0/18	Time: μ=7.102 σ=9.323 Clicks: μ=0.185 σ=0.327 Skips: 0/18	Time: μ=3.401 σ=0.760 Clicks: μ=0.019 σ=0.041 Skips: 0/18
Large Spheres, 4m	Time: μ=2.164 σ=0.533 Clicks: μ=0.000 σ=0.000 Skips: 0/18	Time: μ=4.842 σ=2.237 Clicks: μ=0.160 σ=0.157 Skips: 2/18	Time: μ=3.336 σ=0.542 Clicks: μ=0.031 σ=0.072 Skips: 0/18
Large Spheres, 8m	Time: μ=3.018 σ=0.942 Clicks: μ=0.019 σ=0.041 Skips: 0/18	Time: μ=7.028 σ=4.560 Clicks: μ=0.586 σ=0.578 Skips: 7/18	Time: μ=3.588 σ=0.830 Clicks: μ=0.049 σ=0.092 Skips: 0/18

tests to assess the significance of the fixed effects in the model. We calculated Bonferroni-corrected contrasts using the `emmeans` package when we found significant main effects. Given the non-parametric nature of the questionnaire data, we employed the Friedman test as an omnibus test and the Wilcoxon test with a Bonferroni p-value correction for pairwise comparisons.

4.5 Results

For each target distance, we analyzed each technique to determine their performance. In some cases of the selection tasks, some participants were unable to make any progress in selecting targets. To avoid fatigue, we allowed participants the option to "skip" the selection task if they had spent more than 2 minutes on a task with no significant progress. We report the number of these skipped tasks, although we are unable to incorporate them into the rest of our quantitative analysis. Overall, our results indicate that participants had comparable performance regarding target selection time and the number of missclicks with *Go-Go* and Z-Squish for both small and large spheres. However, both of these techniques outperformed XYZ-Squish in both metrics for both small and large spheres. Moreover, while there is a difference in a target selection time for *Go-Go* for different sphere sizes (larger spheres are selected faster), there is no such difference for Z-Squish, which indicates that target size does not play a big role for Z-Squish. The number of missclicks was comparable between *Go-Go* and *Z-Squish*, but higher for *XYZ-Squish* for all tested distances and sizes. We outline these results in detail in the following.

4.5.1 Target selection time. A summary of results for the Selection task can be found in table 1 and Figure 4 and 5. We found that participants were faster selecting targets using Go-Go and Z-Squish techniques than XYZ-Squish. This finding was supported by the statistically significant main effect for the technique ($F(2, 248.03) = 41.52, p < 0.001, \eta^2 = 0.25$). The post-hoc analysis has shown statistically significant differences between XYZ-Squish and *Go-Go* ($p < 0.001$) as well as Z-Squish ($p < 0.001$) but not between *Go-Go* and Z-Squish ($p = 0.61$). We also found that participants were faster selecting targets at 3 and 4 meters than at 8 meters distances. This finding was supported by the statistically significant main effect for the distance ($F(2, 244.19) = 7.04, p < 0.01, \eta^2 = 0.05$). The post-hoc analysis has shown statistically significant differences between 8 and 3 ($p < 0.001$) as well as 4 meters ($p < 0.001$) but not between 3 and 4 meters ($p = 0.13$). Similarly, participants were faster selecting targets within clouds of larger spheres than smaller. This finding was supported by the statistically significant main effect for the size ($F(1, 247.52) = 43.8, p < 0.001, \eta^2 = 0.15$).

As for the interaction effects, we found a statistically significant interaction effect for technique * size ($F(2, 246.13) = 5.83, p < 0.01, \eta^2 = 0.05$). The post-hoc analysis has shown statistically significant differences between all pairs ($p < 0.01$). This indicates that *Go-Go* outperforms other two techniques for both sizes and smaller sizes lead to longer selection times except for the following pairs: small spheres *Go-Go* and Z-Squish ($p = 0.99$), *Go-Go* small spheres and XYZ-Squish large spheres ($p = 0.07$), *Go-Go* small spheres and Z-Squish large spheres ($p = 0.2$), Z-Squish small and large spheres ($p = 0.32$), large spheres *Go-Go* and Z-Squish ($p = 0.58$).

We did not find the interaction effect for technique * distance to be statistically significant ($F(4, 246.76) = 2.25, p = 0.064$). This is possibly due to the lack of data for XYZ-Squish. However, a comparison between only *Go-Go* and Z-Squish showed technique * distance to be statistically significant ($F(2, 188.05) = 10.17, p < 0.001$). Averaged over both sizes of target, a post-hoc analysis showed statistically significant differences between short (3m/4m) and long (8m) distances for *Go-Go* ($p < 0.001$), but not for Z-Squish ($p > 0.5$).

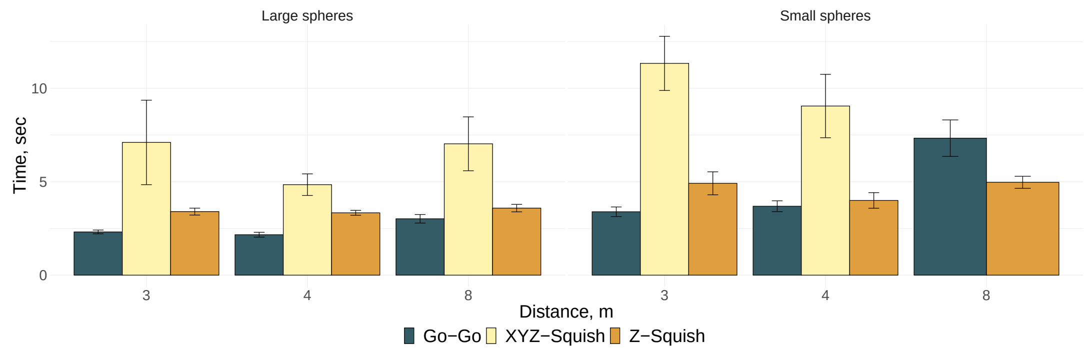


Figure 4: Target selection time for small and large spheres. Data participants who were unable to complete a given task are excluded. Whisker bars show the standard deviation. The fully skipped category (XYZ-Squish, small 8m) is not shown because participants could not finish it due to the high complexity of the task.

Go-Go performed better than Z-Squish at 3m ($p < 0.01$), and no significant difference was found at 4m or 8m ($p > 0.1$) when averaged over both target sizes. For small spheres at 8m, Z-Squish significantly outperformed *Go-Go* ($p < 0.05$).

4.5.2 Missclicks. We found that participants had more missclicks using XYZ-Squish than Z-Squish and *Go-Go*. This finding was supported by the statistically significant main effect for the technique ($\chi^2(2) = 111.1, p < 0.001$). The post-hoc analysis has shown statistically significant differences between XYZ-Squish and *Go-Go* ($p < 0.001$) as well as Z-Squish ($p < 0.001$) but not between *Go-Go* and Z-Squish ($p = 0.77$). We also found that participants had less missclicks at 3 and 4 meters than at 8 meters distances. This finding was supported by the statistically significant main effect for the distance ($\chi^2(2) = 10.5, p < 0.01$). The post-hoc analysis has shown statistically significant differences between 8 and 3 ($p < 0.05$) as well as 4 meters ($p < 0.05$) but not between 3 and 4 meters ($p = 0.92$). Similarly, participants had more missclicks with smaller than larger spheres. This finding was supported by the statistically significant main effect for the size ($\chi^2(1) = 77.6, p < 0.01$). However, we did not observe any statistically significant interaction effects ($p > 0.05$).

4.6 Survey Results: Preferences, Mental load, Embodiment

A summary of results for the survey can be found in the appendix. When asked if they liked performing the task using the technique, participant preferred *Go-Go* (μ=5.444 σ=1.165) the most, followed by *Z-Squish* (μ=4.889 σ=1.487), *XYZ-Squish* (μ=2.111 σ=1.149). This finding was shown statistically significant ($\chi^2(4) = 49.2, p < 0.001$), and the pairwise comparisons showed significant differences between the following pairs: *Go-Go* and *XYZ-Squish* ($p < 0.001$), *XYZ-Squish* and *Z-Squish* ($p < 0.001$).

As for the mental load, when asked if they had to work hard when using the technique, the mean scores were lowest for *Go-Go* (μ=4.111 σ=1.100), followed by *XYZ-Squish* (μ=6.111 σ=1.149) and *Z-Squish* (μ=4.333 σ=1.700). This finding was shown statistically significant ($\chi^2(4) = 18.9, p < 0.001$), and the pairwise comparisons showed significant differences between the following pairs: *Go-Go* and *XYZ-Squish* ($p < 0.001$), *XYZ-Squish* and *Z-Squish* ($p < 0.005$). In summary of the rest of the results, XYZ-Squish scored significantly worse than Go-Go on all statements besides "The pace of the task felt hurried or rushed".Z-Squish did not score significantly different on any questions than Go-Go but had a higher standard deviation on all questions.

The mean embodiment scores were comparable among all techniques: *Go-Go* (μ=9.233 σ=3.583), *XYZ-Squish* (μ=8.885 σ=3.835), *Z-Squish* (μ=9.815 σ=3.635). However, we found no statistically significant difference between these results nor any significant difference between any of the four subscores.

5 Illusory Threshold Study

Initial experimentation with the XYZ-Squish technique suggested that it could be an illusory interaction at certain scaling factors. To quantify this, we adapted the illusory threshold test used by Steinicke et al. [29]. We aimed to find the illusory threshold of the XYZ-Squish interaction using the Go-Go interaction as a baseline.

5.1 Participants

We recruited 18 participants (6 F, 12 M) aged between 21 and 38 ($M = 28.1, SD = 5.4$). Two had never used VR before, 11 – a few times, four – many times, and one – regularly.

5.2 Study design

Participants are first presented with a baseline version of the interaction with a scalar multiplier of 1 for a given selection technique. After also viewing interactions with 100x and $\frac{1}{100}$x scalars as examples of clear greater and lesser reaches, participants were presented with a series of scenes in which the technique is activated with different scalar multipliers and are tasked with determining whether the scalar is greater or lower than the baseline. The **Illusory Threshold** of the interaction is defined as the scalar values at which users can make this prediction correctly 75% of the time. In pilot studies, Z-Squish appeared to have an illusory threshold radius near 0, so it was removed for the sake of time and user fatigue. For both interactions, we used the same scene as for the selection task; however, the target spheres were placed outside the reach of

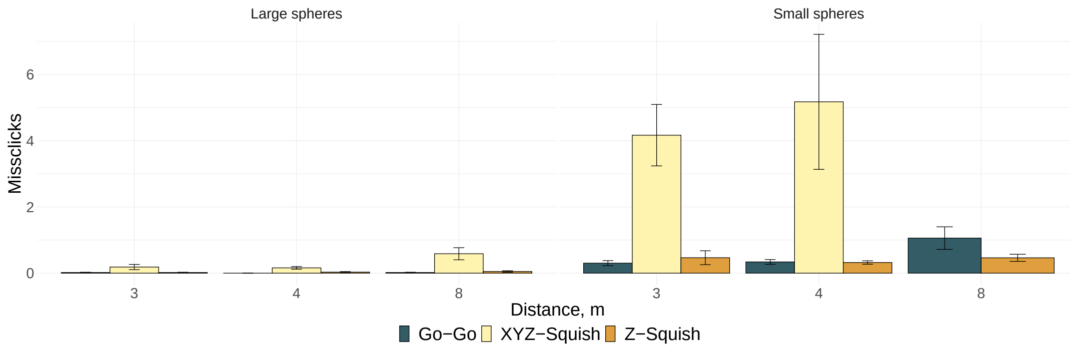


Figure 5: Number of missclicks for small and large spheres. Data participants who were unable to complete a given task are excluded. Whisker bars show the standard deviation. The fully skipped category (XYZ-Squish, small 8m) is not shown because participants could not finish it due to the high complexity of the task.

participants. This was done to prevent participants from determining the interaction reach by assessing how many spheres were in the selection range. Participants were presented with four evenly spaced scalar multipliers greater than 1, and 4 scalar multipliers that were their multiplicative inverse. No 1x multipliers were included in the test. Multipliers were selected based on pilot studies. In each case, participants were asked whether the multiplier appeared to be *greater* or *lesser than* 1. 10 instances of interactions with each multiplier were shuffled into a list, for 80 total guesses. The screen was blacked out briefly between interaction instances. We use the method provided by Steinicke et. al. [29] to determine the illusory threshold. For each multiplier, the fraction of *"Greater than 1"* responses from each participant was plotted, and a sigmoid function was fitted to the data. The illusory threshold for the interaction is defined as the point at which the sigmoid crosses the 0.75 value, meaning that they had a 75% chance of correctly identifying the remapping was increasing their virtual reach.

5.3 Results

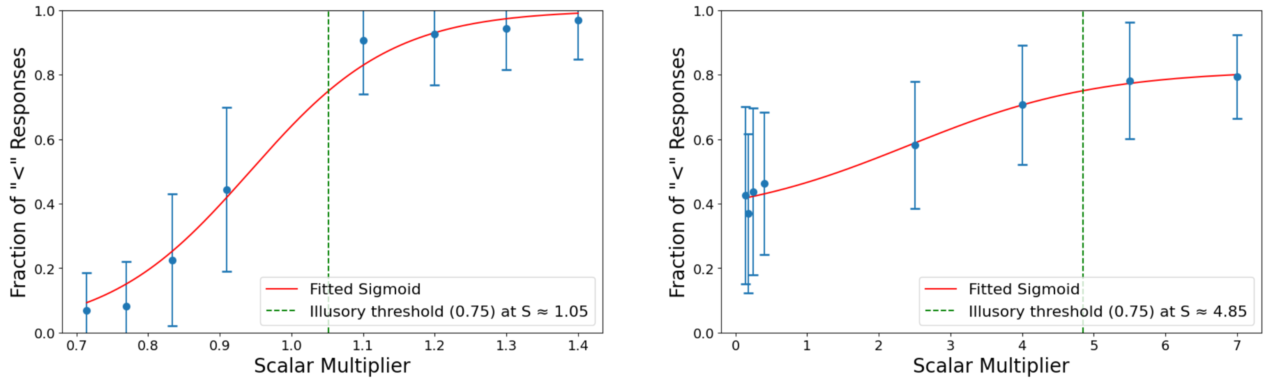
The results at each distance and the threshold analysis for each technique are plotted in Figure 6. Two participants could not detect any change in the XYZ-Squish technique at any scale factor. They claimed to have randomly guessed all interactions, and there is no correlation between their guess results and the scale factor. In these cases, either the participants' illusory threshold must be higher than the maximum value tested (7x), or the participant did not fully understand the task. We followed Steinicke et al.'s method [29] and removed these studies from our dataset. In effect, the average illusory threshold may be above what we report, although we observe a significant increase in the threshold in either case. Among participants who could detect some change in interaction, fitting a sigmoid function to the illusory detection results gives an estimated detection threshold of 1.05 for the Go-Go interaction and 4.85 for the XYZ-Squish interaction. The Go-Go detection radius near 0 is expected since any change in the scalar value results in a visual change in the virtual arm as it stretches from its baseline. The XYZ-Squish threshold is notable in that it exceeds the range at which the interaction is usable as a selection tool.

6 Discussion and Future Work

Our initial hypothesis was that modifying the signifier of a remapping interaction would produce positive effects on performance separate from the mechanical effects of the remapping. We found that performance was improved in some cases, e.g., Z-Squish outperforming Go-Go at long distances. Furthermore, as evidenced by XYZ-Squish's high illusory threshold but poor usability, benefits from modifying the signifier can have major side effects. Overall, our results indicate that alternate signifiers for remappings produce novel interaction techniques

6.1 Squeeze the World or Extend Avatars?

Both of the new interaction techniques use signifiers based on world distortion. Such signifiers are conceptually straightforward and have similar implementations. This similarity, however, does not lead to similar performance. Our evaluation has shown that Z-Squish performed similarly to Go-Go in most cases, while XYZ-Squish performed considerably worse, except for having a higher illusory threshold. The world distortion interactions tended to score worse on survey questions taken from the NASA TLX and on the 'likability' question, but never to a significant level across all interactions. The underlying concept of the signifier cannot fully explain any part of the interaction's performance or survey results. A more promising approach to explain how the signifier changes affect the interaction is to compare the properties of the signifier to existing interactions. Z-Squish effectively magnifies the size of any target to be the same size in the user's visual field, regardless of distance. This provides a comparative advantage when the targets form a small visual arc and a disadvantage when the targets form a large visual arc (since the user can see relatively fewer targets at once). Put another way, the Go-Go technique has two limitations regarding its maximum reach: a mechanical limitation, as the gain placed on hand movements at some distance would decrease accuracy, and a visual limitation, as users have difficulty looking at targets that are far away. Z-Squish has no effect on the mechanical limitation, but removes this visual one. Since the visual limitation is stricter, this significantly increases the effective reach of the interaction. Z-Squish still cannot reach infinitely far due to the mechanical limit, and cannot see objects if they are fully occluded. However,



(a) Go-Go Threshold **(b) XYZ-Squish Threshold**

Figure 6: Illusory threshold analysis of the Go-Go and XYZ-Squish interactions with error bars as one standard deviation.

the fact that effective reach can be increased using nothing but visual changes is significant. XYZ-Squish removes most signifiers of the interaction. This allows it to be illusory for some scale factors, but at a significant performance cost, as there are fewer visual cues as to the cursor's position.

The Go-Go interaction is continuous, meaning it maps similar inputs in physical space to similar outputs in virtual space; and Injective, meaning each action/pose in virtual space can be caused by exactly one action/pose in physical space. This allows us to implement the exocentric functions as global vertex shaders, but modifying signifiers this way is not generally necessary. For instance, the Ninja Hands interaction maps the user's hand onto multiple world points [26], and the OVRlap interaction maps multiple virtual world areas into the user's vision [27]. These signifiers are nearly ego/exocentric inverses of each other. Designers could separate the signifier and the remapping of XR interactions when choosing the interaction for a specific scenario. For example, the Go-Go interaction has a simple mechanic but is limited in its effective reach by the visual angle of its target area. The Poros and PORTAL interactions have a longer effective reach but a relatively more complex 2-stage mechanic (placing the mark/portal and then reaching through it). However, they can reach further targets accurately [12, 24]. We understand that this ability results from both the mechanical resolution of manipulation and proprioception once the portal/mark is placed and the visual signifier that magnifies the interaction area. This signifier can be "applied" to Go-Go while preserving its simpler mechanics. Indeed, Z-Squish's visual magnification is similar to PORTAL's and can increase Go-Go's effective reach (see an example in Table 2).

6.2 Signifiers and Remappings

The full implementation (mechanical remapping and signifier) of any interaction contributes to a "metaphor" or mental model that users utilize to understand the interaction. Presenting and comparing VR interaction techniques through a metaphor-focused lens has proven useful in prior work. For instance, several studies have shown how slight mechanical modifications produce a family of "World in Miniature" interactions for tasks from selection to manipulation to locomotion [7, 20]. A similar approach focusing on families of interactions with similar signifiers could lead to broader categories that may still be helpful for design. Metaphor-based descriptions can conflate the mechanical remapping of an interaction with its signifiers, e.g., "Go-Go stretches your arms out" as opposed to "Go-Go increases the distance from your head to your cursor, and this is visualized by your arm stretching out". Signifiers and remappings can often be separated, which could lead to a new perspective on the relationships between VR user interactions (Figure 7).

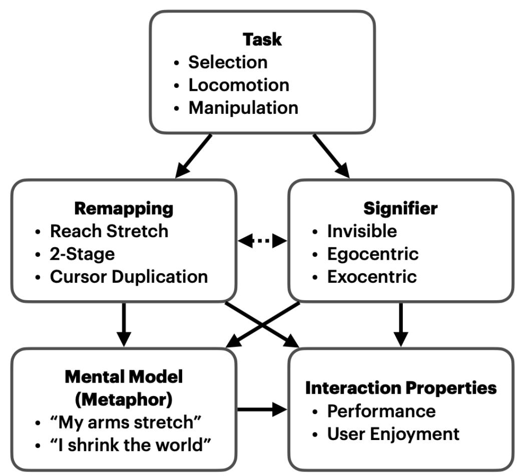


Figure 7: Model of the influence different parts of a VR interaction have during the design process. The given task makes certain requirements of the remapping and possibly the signifier. Some remapping and signifiers cannot reasonably be used together, but many can. Both the remapping and the signifier contribute to a mental model of the interaction, and the mental model, signifier, and remapping all determine the performance qualities of the interaction.

Through the evaluated interaction techniques, it is clear that we can choose the interaction signifier independently of its mechanical

Table 2: Relations of Interactions based on mechanics and properties of signifiers. Standard Preconception refers to the the effect explored by Mine et al. where the world is distorted such that the user can complete their task using preconception [20]. XYZ-Squish and Z-Squish do not qualify since they continuously distort the world as the user moves. Target Magnification refers to world distortions that increase the size of target objects.

	Egocentric	Exocentric: Standard Preconception	Exocentric: Target Magnification	Invisible
Reach Stretch	Go-Go [25]		Z-Squish	XYZ-Squish
2-stage		Scaled-World Grab [20]	Poros [24] PORTAL [12]	
Cursor Duplication	Ninja Hands [26]	OVRlap [27]		

remapping. Treating signifiers as conferring some attributes to an interaction explains the usability study results. However, we made this connection once the study analysis was complete, and it is unclear if this is generally true. Future studies comparing interactions with identical remapping/signifiers could help refine a model of how signifiers affect the properties of an interaction. Given a known XR task, designers could start with an interaction that can mechanically complete the task, and then explore alternate signifiers to improve performance or better match the application's themes. For example, in a world exploration app, Z-Squish's magnification may be useful when selecting distant and detailed locations on a map, while Go-Go's egocentrism is beneficial if designers want the world to feel concrete. If signifiers tend to confer predictable attributes onto interactions, a large-scale categorization of interaction techniques by their signifiers and remappings (like in Table 2) could be helpful to VR designers, as the properties of interactions in empty cells could be inferred based on the properties of interactions in the same row/column. The remappings and signifier properties (Table 2) comprise only a small fraction of prior work. Large-scale databases exist for VR interaction techniques [2, 8]. However, these databases have limited information on the signifiers' properties. Moreover, there is no consistent set of signifier categories to use. Future work, determining a valuable set of categories and compiling a large-scale table, could aid designers in determining which techniques to use for a given situation.

7 Limitations

Since the XYZ-Squish interaction is mechanically identical to the Go-Go and Z-Squish interactions, it results in the cursor shrinking in size relative to the visual hand and becoming occluded as the hand is extended. We suspect that this played a significant role in XYZ-Squish's poor performance and it could be improved by keeping the cursor fixed in size relative to the visual hand, or by making the cursor shrink to the tip of a finger so that it stays unoccluded. Such an interaction would no longer strictly belong to the "Go-Go family" of interactions but would likely remain illusory within some radius. Due to the method of occluding targets with spheres, our usability study did not fully test selection performance in the range where XYZ-Squish is illusory. The interaction performed best with large targets at a 3m distance, and it follows that performance would improve at smaller distances, but the exact performance values are unknown. An illusory scaling interaction that allows for rendering a virtual arm is interesting in its own right and could be used to accommodate users of different arm lengths to specific avatar models. We encourage future work to investigate this further. The high number of skipped tasks of XYZ-Squish on certain selections limited the number of valid data points that could be used in calculating its actual performance. In this case, we believe that categorizing XYZ-Squish as "essentially unusable" and significantly worse than the alternatives is sufficient for our conclusions; however, any future work that needs precise performance values for this version of XYZ-Squish would require additional data. Since we only tested a simple sphere-selection task, our study missed the opportunity to address how these techniques would perform in complex, realistic applications. We provide novel insights into the techniques' performance and leave the granular exploration of complex environments for future work. Additionally, our study did not test older participants, which would be beneficial for future work. Finally, we limited our study to quantitative metrics and will run future studies focusing on the qualitative data to understand the reasons behind our performance metrics better. Given the signifiers' major effect on performance, we expect a qualitative study of user reactions to be fruitful future work.

8 Conclusion

In this paper, we created two new interaction techniques (Z-Squish and XYZ-Squish) with identical mechanical mappings to an existing technique (Go-Go) but with different signifiers. We investigated their performance, interaction, and perception through usability and illusory detection studies. Our results indicate that Z-Squish and Go-Go perform similarly for small and large target spheres, and that sphere distance and size do not significantly impact Z-Squish's performance, although it does impact Go-Go's. Compared to the Go-Go, Z-Squish resulted in longer selection times by 1.1-1.4 seconds if the selection targets were large (60cm) or nearby (3m) but resulted in shorter selection times by 3.2 seconds if the selection targets were small (10cm) and distant (8m). Additionally, XYZ-Squish is illusory up to a 4.85x reach modifier, although at a significant performance cost. With this, we propose that separating mechanics from signifiers can be useful for researchers and designers creating new VR interactions, as it can lead to novel interaction techniques.

References

[1] Parastoo Abtahi and Sean Follmer. 2018. Visuo-Haptic Illusions for Improving the Perceived Performance of Shape Displays. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173724

[2] Parastoo Abtahi, Sidney Q. Hough, James A. Landay, and Sean Follmer. 2022. Beyond Being Real: A Sensorimotor Control Perspective on Interactions in Virtual

Reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 358, 17 pages. https://doi.org/10.1145/3491102.3517706

[3] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 chi conference on human factors in computing systems*. 1968–1979.

[4] Frank A. Biocca and J.P. Rolland. 1998. Virtual Eyes Can Rearrange Your Body: Adaptation to Visual Displacement in See-Through, Head-Mounted Displays. *Presence: Teleoperators and Virtual Environments* 7, 3 (06 1998), 262–277. https://doi.org/10.1162/105474698565703 arXiv:https://direct.mit.edu/pvar/article-pdf/7/3/262/1836431/105474698565703.pdf

[5] Han Joo Chae, Jeong-in Hwang, and Jinwook Seo. 2018. Wall-based Space Manipulation Technique for Efficient Placement of Distant Objects in Augmented Reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 45–52. https://doi.org/10.1145/3242587.3242631

[6] CRAN. 2020. LmerTest: Tests in linear mixed effects models. https://CRAN.R-project.org/package=lmerTest

[7] Kurtis Danyluk, Barrett Ens, Bernhard Jenny, and Wesley Willett. 2021. A Design Space Exploration of Worlds in Miniature. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 122, 15 pages. https://doi.org/10.1145/3411764.3445098

[8] Massimiliano Di Luca, Hasti Seifi, Simon Egan, and Mar Gonzalez-Franco. 2021. Locomotion Vault: the Extra Mile in Analyzing VR Locomotion Techniques. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 128, 10 pages. https://doi.org/10.1145/3411764.3445319

[9] Eric J Gonzalez, Parastoo Abtahi, and Sean Follmer. 2020. Reach+ extending the reachability of encountered-type haptics devices through dynamic redirection in vr. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 236–248.

[10] Eric J Gonzalez, Elyse DZ Chase, Pramod Kotipalli, and Sean Follmer. 2022. A model predictive control approach for reach redirection in virtual reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–15.

[11] Eric J Gonzalez and Sean Follmer. 2023. Sensorimotor Simulation of Redirected Reaching using Stochastic Optimal Feedback Control. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 776, 17 pages. https://doi.org/10.1145/3544548.3580767

[12] Dongyun Han, Donghoon Kim, and Isaac Cho. 2022. PORTAL: Portal Widget for Remote Target Acquisition and Control in Immersive Virtual Environments. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology* (Tsukuba, Japan) *(VRST '22)*. Association for Computing Machinery, New York, NY, USA, Article 16, 11 pages. https://doi.org/10.1145/3562939.3565639

[13] David Hecht and Miriam Reiner. 2009. Sensory dominance in combinations of audio, visual and haptic stimuli. *Experimental brain research* 193 (2009), 307–314. https://doi.org/10.1007/s00221-008-1626-z

[14] Victoria Interrante, Brian Ries, and Lee Anderson. 2007. Seven League Boots: A New Metaphor for Augmented Locomotion through Moderately Large Scale Immersive Virtual Environments. In *2007 IEEE Symposium on 3D User Interfaces*. https://doi.org/10.1109/3DUI.2007.340791

[15] PM Jaekl, MR Jenkin, and Laurence R Harris. 2005. Perceiving a stable world during active rotational and translational head movements. *Experimental brain research* 163 (2005), 388–399. https://doi.org/10.1007/s00221-004-2191-8

[16] Luv Kohli. 2010. Redirected touching: Warping space to remap passive haptics. In *2010 IEEE Symposium on 3D User Interfaces (3DUI)*. 129–130. https://doi.org/10.1109/3DUI.2010.5444703

[17] Nianlong Li, Zhengquan Zhang, Can Liu, Zengyao Yang, Yinan Fu, Feng Tian, Teng Han, and Mingming Fan. 2021. vMirror: Enhancing the Interaction with Occluded or Distant Objects in VR with Virtual Mirrors. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 132, 11 pages. https://doi.org/10.1145/3411764.3445537

[18] Eva Mackamul, Géry Casiez, and Sylvain Malacria. 2023. Exploring visual signifier characteristics to improve the perception of affordances of in-place touch inputs. *Proceedings of the ACM on Human-Computer Interaction* 7, MHCI (2023), 1–32.

[19] Jess McIntosh, Hubert Dariusz Zajac, Andreea Nicoleta Stefan, Joanna Bergström, and Kasper Hornbæk. 2020. Iteratively Adapting Avatars using Task-Integrated Optimisation. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 709–721. https://doi.org/10.1145/3379337.3415832

[20] Mark R. Mine, Frederick P. Brooks, and Carlo H. Sequin. 1997. Moving objects in space: exploiting proprioception in virtual-environment interaction. In *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '97)*. ACM Press/Addison-Wesley Publishing Co., USA, 19–26. https://doi.org/10.1145/258734.258747

[21] Reiji Miura, Shunichi Kasahara, Michiteru Kitazaki, Adrien Verhulst, Masahiko Inami, and Maki Sugimoto. 2022. MultiSoma: Motor and Gaze Analysis on Distributed Embodiment With Synchronized Behavior and Perception. *Frontiers in Computer Science* 4 (2022). https://doi.org/10.3389/fcomp.2022.788014

[22] Vivek C Nair, Gonzalo Munilla-Garrido, and Dawn Song. 2023. Going Incognito in the Metaverse: Achieving Theoretically Optimal Privacy-Usability Tradeoffs in VR. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 61, 16 pages. https://doi.org/10.1145/3586183.3606754

[23] Tabitha C Peck and Mar Gonzalez-Franco. 2021. Avatar embodiment. a standardized questionnaire. *Frontiers in Virtual Reality* 1 (2021), 575943.

[24] Henning Pohl, Klemen Lilija, Jess McIntosh, and Kasper Hornbæk. 2021. Poros: Configurable Proxies for Distant Interactions in VR. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 532, 12 pages. https://doi.org/10.1145/3411764.3445685

[25] Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 1996. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In *Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology* (Seattle, Washington, USA) *(UIST '96)*. Association for Computing Machinery, New York, NY, USA, 79–80. https://doi.org/10.1145/237091.237102

[26] Jonas Schjerlund, Kasper Hornbæk, and Joanna Bergström. 2021. Ninja Hands: Using Many Hands to Improve Target Selection in VR. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 130, 14 pages. https://doi.org/10.1145/3411764.3445759

[27] Jonas Schjerlund, Kasper Hornbæk, and Joanna Bergström. 2022. OVRlap: Perceiving Multiple Locations Simultaneously to Improve Interaction in VR. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 355, 13 pages. https://doi.org/10.1145/3491102.3501873

[28] Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2008. Analyses of human sensitivity to redirected walking. In *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology* (Bordeaux, France) *(VRST '08)*. Association for Computing Machinery, New York, NY, USA, 149–156. https://doi.org/10.1145/1450579.1450611

[29] Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2010. Estimation of Detection Thresholds for Redirected Walking Techniques. *IEEE Transactions on Visualization and Computer Graphics* 16, 1 (2010), 17–27. https://doi.org/10.1109/TVCG.2009.62

[30] Frank Steinicke, Gerd Bruder, Timo Ropinski, and Klaus Hinrichs. 2008. Moving towards generally applicable redirected walking.

[31] Richard Stoakley, Matthew J. Conway, and Randy Pausch. 1995. Virtual reality on a WIM: interactive worlds in miniature. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '95)*. ACM Press/Addison-Wesley Publishing Co., USA, 265–272. https://doi.org/10.1145/223904.223938

[32] Andrea Stevenson Won, Jeremy Bailenson, Jimmy Lee, and Jaron Lanier. 2015. Homuncular Flexibility in Virtual Reality. *Journal of Computer-Mediated Communication* 20, 3 (01 2015), 241–259. https://doi.org/10.1111/jcc4.12107 arXiv:https://academic.oup.com/jcmc/article-pdf/20/3/241/19492300/jjcmcom0241.pdf

[33] Andrea Stevenson Won, Jeremy N Bailenson, and Jaron Lanier. 2015. Homuncular flexibility: the human ability to inhabit nonhuman avatars. *Emerging Trends in the Social and Behavioral Sciences: An Interdisciplinary, Searchable, and Linkable Resource* (2015), 1–16.

[34] Xianshi Xie, Qiufeng Lin, Haojie Wu, Gayathri Narasimham, Timothy P. McNamara, John Rieser, and Bobby Bodenheimer. 2010. A system for exploring large virtual environments that combines scaled translational gain and interventions. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization* (Los Angeles, California) *(APGV '10)*. Association for Computing Machinery, New York, NY, USA, 65–72. https://doi.org/10.1145/1836248.1836260

[35] Futian Zhang, Keiko Katsuragawa, and Edward Lank. 2022. Conductor: Intersection-Based Bimanual Pointing in Augmented and Virtual Reality. *Proc. ACM Hum.-Comput. Interact.* 6, ISS, Article 560 (nov 2022), 15 pages. https://doi.org/10.1145/3567713

[36] Yiwei Zhao and Sean Follmer. 2018. A Functional Optimization Based Approach for Continuous 3D Retargeted Touch of Arbitrary, Complex Boundaries in Haptic Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174118