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ORIGINAL ARTICLE

Reaching further in VR: a comparative study with a novel velocity-based technique

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Abstract
Out-of-reach interaction in virtual reality has primarily relied on raycasting (selection using the laser pointer metaphor). However, as bare-hand tracking becomes increasingly prevalent, there is a growing need to explore and optimize hand-based out-of-reach interaction techniques. To address this, we introduce Hand Gliding and Laser Gliding, novel out-of-reach interaction techniques that use velocity-to-velocity mapping to control virtual hands through physical movements, and implement Go-Go and HOMER, position-to-position methods. First, a pilot study evaluated the feasibility of Hand Gliding. Next, we conducted a within-subject comparison of the four interaction techniques using selection and translation tasks while assessing speed, comfort, and subjective responses. The best results were achieved with both raycasting-aided techniques (HOMER, Laser Gliding) in terms of both performance and user comfort. Position-to-position mapping performed slightly better in tasks requiring rapid selection, while velocity-to-velocity techniques facilitated interaction at greater distances. The feasibility of velocity-to-velocity approaches to out-of-reach interaction was confirmed by this study. Due to their simple implementation (compared to position-based techniques, they do not require torso tracking data), velocity-based interaction methods have the potential for wide adoption in current VR systems.

Keywords Out-of-reach Interaction · Hand-Based Interaction · Bare-Hand Interaction · Virtual Reality · Velocity-to-Velocity Control

1 Introduction

Virtual reality (VR) environments enable users to visit virtual spaces of arbitrary extent while being physically confined to a smaller room. One of the fundamental challenges in VR interaction is mapping this limited physical space to an extensive virtual world. Locomotion techniques (Boletsis 2017) address this issue by allowing the user's virtual representation (avatar) to move within the VR scene without requiring corresponding physical movement or by scaling small physical movements. Alternatively, interaction techniques can maintain the avatar's position while extending the range of manual interactions beyond the user's natural arm reach.

Out-of-reach interaction techniques enable users to manipulate objects while remaining stationary, preserving spatial context. This is particularly advantageous for scenarios involving interactions with menus, two-dimensional surfaces, or sets of objects logically and spatially anchored in one place. Examples include virtual workplaces, chat interfaces, and other stationary (seated) VR setups. Many VR users are already familiar with out-of-reach interaction, as it is commonly encountered in VR 'home' environments used for configuring settings and launching applications.

The most common out-of-reach interaction technique is raycasting (Gabel et al. 2023; Wentzel et al. 2024), where a ray extends from the user's VR controller, and interactions occur at the intersection of the ray and virtual objects (Argelaguet and Andujar 2013). While effective for object selection, raycasting has notable limitations. It is not well-suited for precise object manipulation (Bowman and Hodges 1997) or for selecting small or distant objects (Mine et al. 1997; Poupyrev and Ichikawa 1999). To mitigate these

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issues, various extensions have been proposed, such as Depth Ray (Grossman and Balakrishnan 2006), RayCursor (Baloup et al. 2019), FanRay (Wei et al. 2023), or GazeRayCursor (Chen et al. 2023).

Beyond raycasting, early VR research explored hand-based interaction using specialized gloves (Poupyrev and Ichikawa 1999). Two notable techniques for extending hand reach in VR are *Go-Go* and *HOMER*. Go-Go (Poupyrev et al. 1996) enables users to reach distant objects by applying a nonlinear 'growth' function that effectively extends the avatar's arm. This technique allows users to intuitively reach farther by moving their physical hand outward, but it also results in arm fatigue due to unnatural postures, commonly known as the 'gorilla arm' effect. HOMER (Bowman and Hodges 1997) combines raycasting for object selection with position-based scaling, mapping the virtual hand's reach to the user's real-world hand movement. HOMER mitigates some of Go-Go's fatigue issues but still leads to poor precision when interacting with small or distant objects due to the upscaling of hand movements.

Advances in camera-based hand tracking, powered by computer vision and machine learning-driven pose estimation (Han et al. 2020), have enabled modern VR systems to eliminate the need for handheld controllers or specialized gloves, allowing for natural and direct interaction through hand gestures. This shift necessitates exploring alternative hand-based out-of-reach interaction techniques and reassessing established methods like Go-Go and HOMER, particularly concerning their precision limitations.

In response to these challenges, we introduce *Hand Gliding*, a velocity-to-velocity interaction technique designed to leverage bare-hand tracking for intuitive and precise manipulation of distant objects. Hand Gliding enables users to reposition their virtual hands toward remote targets by moving them in the target's direction. The technique employs velocity-based control to 'steer' the virtual hand away from alignment with the physical hand through faster movements. Once the target is reached, users can interact with fine precision using slower movements or deactivate the technique and return to position-to-position mapping while maintaining interactions at a distance.

Building on HOMER, we developed *Laser Gliding*, a Hand Gliding variant that integrates raycasting for initial positioning. Laser Gliding retains velocity-based mapping for natural interactions with distant objects while providing rapid targeting assistance through ray guidance.

In this study, we introduce, implement, and evaluate Hand Gliding, a novel velocity-to-velocity hand-based out-of-reach interaction approach, validated through a pilot study. Second, we conducted a systematic within-subject comparison of Hand Gliding, Laser Gliding, and contemporary implementations of Go-Go and HOMER. By empirically examining the interaction techniques on a series of VR tasks, we provide insights into performance metrics such as task completion times and speed of hand positioning, as well as subjective metrics such as user comfort.

These findings contribute to the broader understanding of bare-hand out-of-reach interaction techniques in VR and inform the design of future interaction methods aimed at balancing natural hand interactions with precise remote object manipulation.

2 Background

2.1 Theoretical foundations of hand-based interaction

According to *optimized initial impulse model* by Meyer et al. (1988), the movement toward the target in interaction consists typically of two phases. Firstly, the user attempts to reach the target with a fast and inaccurate movement (the ballistic phase). In case the target was not acquired, iterative slow correction movements follow in the second stage of target acquisition. Meyer's model extends *Fitts' law*, a well-established model of human movement widely used in HCI. Fitts' law has been thoroughly validated across various interaction contexts (Lou et al. 2024), but its original formulation applies to one-dimensional (1D) tasks. While it has been extended to two-dimensional interaction tasks (MacKenzie 1992), its validity in 3D VR environments has been the subject of recent discussion (Batmaz et al. 2018; Clark et al. 2020; Monteiro et al. 2023; Cha et al. 2024; Lou et al. 2024). For example Cha et al. (2024) found that participants demonstrated greater movement speed in the downward direction compared to upward movements and faced significant difficulties when making corrective adjustments in the downward and leftward directions. Additionally, Lou et al. (2024) demonstrated that movement direction angle, arm fatigue, and controller usage affected movement time, while free-hand interactions were less impacted by arm fatigue.

2.2 Methods in amplified hand-based interaction

2.2.1 Manipulating control-to-display ratio

Out-of-reach interaction methods that amplify hand movements make use of changes to the *control-to-display (CD) ratio*. The CD ratio indicates the relationship between the movement of the controller and the cursor–in our case, how much the movement of the physical hand affects the movement of the virtual hand. $CD < 1$ upscales and $CD > 1$ downscales the cursor movement relative to the controller movement (Argelaguet and Andujar 2013). A dynamically changing CD ratio means that the relationship between the physical and virtual hand movements is variable. In the case of the Go-Go, the CD ratio is governed by the distance between the users' hand and their torso. In HOMER, the distance between the user and the hand is mapped to the distance between the user and the virtual hand position (after it is moved by raycasting), scaling the CD accordingly. In our velocity-to-velocity techniques, the CD ratio is governed by the speed of the user's hand movement.

2.2.2 Clutching

For cases when the congruency of a controller decouples from its visual representation, it is important to provide users with a corrective tool. *Clutching* (or ratcheting) (Hinckley et al. 1994) is a functionality allowing the user to recalibrate the position of their physical hand without influencing the virtual hand's position (Ware 1990). Clutching is essential to ensure user comfort during the interaction, and relevant work (Nancel et al. 2015) regarding touchpad interactions demonstrated the favorable and effective use of clutching when it was optional.

2.3 Types of out-of-reach VR interaction

2.3.1 Exocentric and egocentric interactions

The use of intentionally altered user representations for interaction has been explored since the early days of VR (Lanier 2017). Interactions involving extended or altered virtual bodies form the foundation of out-of-reach interaction methods. In their study of multiple VR interaction techniques, Poupyrev and Ichikawa (1999) traced the transition from real-world-constrained manipulation (Ware 1990) to 'supernatural' techniques such as raycasting and Go-Go. They further classified these techniques into *exocentric* and *egocentric* approaches.

Exocentric methods comprise interaction from the 'God's eye viewpoint'–the 3rd person perspective. Examples include scaled-world grab (Mine et al. 1997), which temporarily scales the environment to enhance object reachability, reverting once interaction ends. Similarly, the world-in-miniature (Stoakley et al. 1995) provides a miniature virtual space for interaction. Egocentric methods operate from the user's perspective and are divided into *virtual pointer* techniques (Mine 1995), like raycasting for selecting 3D objects, and *virtual hand* techniques (Poupyrev and Ichikawa 1999), which mimic and extend natural hand interactions.

2.3.2 Interaction from perspective of virtual embodiment

While Poupyrev and Ichikawa's taxonomy considers any 3D selection tool (as opposed to a 1D point) linked to hand tracking as the virtual hand technique (Argelaguet and Andujar 2013), in contemporary VR embracing hand tracking and user embodiment, the term 'virtual hand metaphor' better describes mappings where a virtual hand replica maintains the true hand's morphology.

Egocentric hand-based out-of-reach interaction methods align with the principles of *virtual embodiment* in VR. Embodiment involves the transfer of ownership, agency, and self-location from the physical to the virtual body (Slater et al. 2009; Kilteni et al. 2012; Škola and Liarokapis 2021), typically driven by visuo-motor synchrony between predicted action outcomes and visual feedback in the HMD (Gonzalez-Franco and Lanier 2017; Blanke 2012). Similar to body ownership illusions outside VR (Botvinick and Cohen 1998), partial body ownership transfer commonly occurs even when only hands are rendered in VR (Sanchez-Vives et al. 2010).

Modifying an avatar can maintain the embodiment illusion despite some incongruency with the user's body. This was firstly demonstrated in the earlier days of VR (Lanier 2006), and later formally studied with several illusions manipulating one's sense of body ownership (e.g., Pinocchio illusion (Berger et al. 2022), very long arm illusion (Kilteni et al. 2012), or homuncular flexibility (Won et al. 2015)).

Unlike these illusions, this study explores deliberate, task-dependent changes to avatar's bodily configuration. Given the limited research on body ownership in self-altered avatars, we included an embodiment questionnaire to this investigation.

2.3.3 From reality-based to beyond-real interactions

More recently, Abtahi et al. (2022) categorized movement-based VR interactions into three types: *reality-based*, *illusory*, and *beyond-real methods*. Reality-based interactions closely mimic real-world movements, maintaining a direct 1:1 mapping between physical and virtual actions. Illusory interactions introduce subtle remappings, creating slight discrepancies between actual and virtual movements, designed to remain below the user's perceptual threshold, preserving the illusion of unaltered interaction. Finally, beyond-real interactions deliberately introduce noticeable remappings, enabling experiences unattainable in the physical world.

2.3.4 Beyond-real interactions

Beyond-real interactions possess a distinct and compelling quality, often described as a kind of 'magic' (Slater 1994). For decades, researchers have highlighted the importance of exploring virtual experiences beyond mere replication of reality (Abtahi et al. 2022). For example, Casati and Pasquinelli (2005) advocated for focusing on the creation of virtual perceptual objects with no direct counterparts in physical reality. Bailenson (2018) argued that VR's ability to bend reality enables the creation of experiences unrestricted by real-world laws, allowing users to engage in actions otherwise impossible outside virtual environments. He emphasized that 'VR is perfect for things you couldn't do in the real world'.

Abtahi et al. (2022) classify beyond-real interactions into three categories: *space transformations*, which modify the scale or geometry of the virtual environment to aid navigation or object manipulation; *time transformations*, which adjust the temporal relationship between user actions and virtual outcomes, such as slowing time for precise interactions; and *body transformations*, which alter the user's virtual body, such as extending limbs to reach distant objects. This paper focuses on the latter.

From an interaction design perspective, Abtahi et al. (2022) note that while beyond-real VR interactions can improve efficiency and ergonomics, they also introduce sensory mismatches between real-world and virtual feedback. These discrepancies impact usability, which requires designs that promote learning, adaptation, and user control.

2.4 Hand-based out-of-reach interaction techniques

This section presents hand-based out-of-reach interaction techniques that extend and alter the user's virtual body.

2.4.1 Go-Go

The Go-Go technique, introduced by Poupyrev et al. (1996), employs non-linear mapping between the physical and virtual hand positions. It extends reach by exponentially amplifying the distance between the body and the virtual hand once the physical hand surpasses a threshold (typically 2/3 of the arm's length).

The strength of Go-Go lies in its intuitive mapping to real-world actions—users naturally stretch their arms when reaching for distant objects. However, its modeless nature requires users to keep their arms extended during manipulation, leading to fatigue and reduced precision due to the compression of the motor space (a relatively small motor space controls a much larger control space). Variants of Go-Go include Fast Go-Go (which removes the linear peripersonal space mapping and uses a steeper amplification function) and Stretch Go-Go (where the arm grows at a constant speed, allowing for arbitrary reach) (Bowman and Hodges 1997).

2.4.2 HOMER

The HOMER (Hand-centered Object Manipulation Extending Ray-casting) technique (Bowman and Hodges 1997) uses raycasting for selection, transferring the virtual hand to the target object upon selection. The user-to-hand distance is mapped to the user-to-object distance, allowing for simple positioning of the object within an area bound by the sphere surrounding the user, possibly even further (if the original body-to-hand distance allows for further stretching of the arm). HOMER exploits raycasting for the selection of the hand destination and does not utilize it directly for interaction. After the virtual hand is transferred to the raycasting destination, natural hand-based interaction follows.

2.4.3 Techniques manipulating CD gain

Several techniques manipulate the mapping between controllers and virtual objects, even though full velocity-to-velocity hand-based VR interaction has not yet been implemented. Vogel and Balakrishnan (2005) implemented velocity-to-velocity mapping between free-hand pointing with a tracked hand and a cursor on a distant large screen. Their method amplified hand movements using a non-linear CD gain inspired by Windows XP mouse acceleration, while clutching and raycasting from an extended finger provided additional interaction methods.

In VR, PRISM (Frees et al. 2007) dynamically adjusted CD gain to slow down movements during fine manipulation, effectively employing velocity-based control for error correction. This principle was later extended in Adaptive Pointing (König et al. 2009), with both approaches incorporating mechanisms to maintain congruency between physical and virtual hands. Expanding on these ideas, Pointable (Banerjee et al. 2011) introduced bimanual interaction for tabletops, where the dominant hand selected distant targets while the non-dominant hand adjusted CD gain for transformations. Hybrid approaches also emerged, such as combining Go-Go with PRISM, which improved selection performance (Auteri et al. 2013). Similarly, Wentzel et al. (2020) introduced non-linear amplification of smaller movements, further enhancing user comfort in VR.

2.4.4 Modern adaptations of Go-Go and HOMER

In augmented reality, Feuchtner and Müller (2017) extended Go-Go for manipulation of objects in real-world, addressing challenges such as visual occlusion of the physical arm while preserving body ownership. Hybrid solutions combining Go-Go and HOMER have also been explored, such as in large 3D graph exploration (Zielasko et al. 2018). Studies exploring dual hand representations with Go-Go and PRISM (Dewez et al. 2022) did not show a clear preference or performance increase for duplicated hands. While single-hand representation was generally preferred, Go-Go users exhibited more diverse opinions.

2.4.5 Alternative selection techniques

PRECIOUS (Mendes et al. 2017) introduced a progressive refinement method using cone-casting, which improved precision by iteratively narrowing down object selection. Expanding on alternative selection techniques, ViewfinderVR (Kim and Xiong 2022) employed a customizable virtual viewfinder with a through-the-lens approach, enabling faster and more precise target selection by repositioning the interaction space onto a virtual panel within the user's immediate reach. Another approach to enhancing reach and selection, Ninja Hands (Schjerlund et al. 2021), explored multiple virtual hand representations, testing configurations of up to 64 hands. While selection time did not decrease significantly with more hands, excessive duplication increased decision time, with four to eight hands yielding the best performance. Feuchtner and Müller (2018) introduced Ownershift, a technique that mitigates fatigue in mid-air interactions by gradually shifting the virtual environment instead of the user's hand, allowing for extended interaction while preserving a stable hand reference frame.

2.4.6 Haptic-feedback integration

Researchers have also explored haptic feedback for extended-reach interactions (Achibet et al. 2015; Seo et al. 2023). This remains an important research direction, as freehand interaction often leads to arm fatigue (Lou et al. 2020), which can be alleviated using haptic feedback. Kourtesis et al. (2022) demonstrated that besides enhanced accuracy and user's perceptual experience, electrotactile feedback compensated for the performance loss with free-hand interaction.

Although Seo et al. (2023) only provides descriptive statistics, their study remains relevant, as it examines how hand extension impacts body ownership and agency. Their findings suggest that visuotactile synchrony enhances self-location and body ownership but does not significantly affect agency. However, it's important to note that overall levels of ownership and agency were relatively low (rarely exceeding the midpoint of the scale). This indicates that although users can accept extended virtual limbs as part of their bodies to some extent, their perceived control remains a separate issue.

2.5 Implications for Hand Gliding

In Hand Gliding, our velocity-to-velocity out-of-reach interaction method, the spatial congruency between physical and virtual hand movements is no longer maintained. The velocity-to-velocity mapping decouples the motor space from the interaction space of the controlling hand (Argelaguet and Andujar 2013). As a result, users cannot rely on proprioception and instead must depend on visual feedback (Smith et al. 2000), which is expected when selecting objects beyond arm's reach. Prior evidence suggests that visual feedback dominates the sense of control during movement execution and that users adapt based on this feedback (König et al. 2009). This decoupling of physical and virtual hand congruency also presents an opportunity to mitigate the 'gorilla arm' effect.

Although accuracy and speed are important for evaluating interaction methods, subjective aspects such as ease of acquisition and comfort can be equally critical (Song et al. 2000). Frustration, cognitive load, or the need for extensive training can significantly impact usability (Argelaguet and Andujar 2013), making subjective user experience a key factor in assessing interaction effectiveness. Given these considerations, our study incorporates subjective evaluation to capture aspects of usability that objective performance metrics alone may not fully reflect.

3 Velocity-to-velocity interaction: Hand Gliding

3.1 Description of the technique

Hand Gliding is a novel out-of-reach interaction technique that employs a velocity-to-velocity mapping between the physical and virtual hand. The CD ratio dynamically adjusts based on the speed of the tracked hand, following the optimized initial impulse model (Meyer et al. 1988). During the ballistic phase, movement prioritizes speed over precision, whereas in the corrective phase, precision is favored (Meyer et al. 1988; Argelaguet and Andujar 2013). While velocity-based gain adjustments are widely used in mouse pointer control, to the best of the authors' knowledge, no existing VR interaction technique leverages velocity-to-velocity mapping for amplifying hand movements.

The implementation of Hand Gliding modifies the positioning of virtual hands based on hand tracking data. In each rendered frame of the VR application, the virtual hand offset d is computed iteratively from the offset of the previous frame d_0, the averaged physical hand velocity v (calculated over a fixed number of preceding frames), and sensitivity control coefficients a and b in the following translation function:

$$d = d_0 + \hat{v} \cdot \frac{1 - e^{-a\overline{v}^2}}{b} \quad (1)$$

where $\hat{v}$ is the normalized vector of averaged velocity, and $\overline{v}$ is its magnitude. In our implementation, we set $a = 75$, $b = 7$, and used a two-frame window for averaging v. These parameters were selected empirically in informal pilot testing, to yield smooth virtual hand motion in both ballistic and corrective phase of the movement.

3.2 Evaluation through selection speed

In the rest of this work, we use what we call hand destination selection (HDS), defined as the selection of a new position for the virtual hand in a specific task. HDS refers to the cases where an out-of-reach interaction technique must be used to reposition the hand to facilitate further interaction. The efficiency of selection with Hand Gliding and the other studied techniques was evaluated by computing the hand destination selection speed (HDSS).

$$HDSS = \frac{\text{displacement}}{\text{time}} \left[m * s^{-1}\right] \quad (2)$$

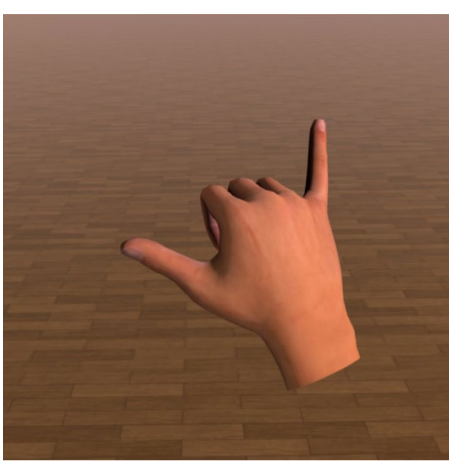

Fig. 1 The activation gesture used in the pilot implementation of Hand Gliding. The users were required to hold the gesture to keep the amplified interaction with Hand Gliding on, and normal hand behavior was restored when the gesture was canceled

Displacement in Equation 2, similar to its definition in physics, refers to the straight-line distance between the starting and destination points, not the actual path taken to reach the destination.

3.3 Specifics of the pilot implementation

Hand Gliding was initially developed in a feasibility study, with its implementation in the main study informed by findings from the pilot phase.

3.3.1 Activation

The technique is activated through a specific gesture. In the pilot implementation, the gesture is sustained throughout the entire duration of hand steering. In the main study, the gesture is used as a toggle, switching the interaction techniques on or off as needed. The gesture employed for the pilot study consisted of an extended thumb and a little finger while keeping the remaining fingers closed (see Fig. 1), which was changed for the full study to a V-gesture (shown in Fig. 3).

3.3.2 Translation function

In the pilot implementation, the velocity of the virtual hand was calculated not only from the velocity of the physical hand but also based on the momentary displacement of the physical hand from the anchor position where the activation gesture was performed. This allowed participants to travel greater distances by keeping their physical hands displaced relative to the anchor position. However, this behavior did not perform well after the activation was changed to toggle mode and was removed in the main study.

4 Pilot study: Hand Gliding feasibility

4.1 Materials and methods

4.1.1 Study design

The pilot study served as a feasibility assessment using a within-subject design to evaluate hand steering speed and interaction effectiveness at varying distances. Performance in Hand Gliding was assessed by measuring improvements in technique usage between the first and second runs of the selection task. Feasibility of interaction at different distances was examined through accuracy loss and increased task time, analyzed using the independent variable *distance* in docking and keypad tasks (set at three levels: near the user, 1.5 m, and 2 m).

4.1.2 Participants

10 participants (6 female, 4 male, median age 33, SD = 4.52) participated in the pilot study. From the original sample (N = 14), two participants had been excluded due to errors in the hand tracking system rendering the VR environment unusable, and another two participants were unable to perform the gesture so the system could recognize it reliably.

4.1.3 Apparatus

The scene was presented using a standalone Meta Quest 2 HMD with resolution 1832 x 1920 per eye, 90Hz refresh rate, 104° horizontal and 98° vertical field of view, weight 503 g, and adjustable inter-pupillary distance with three settings for 58, 63, and 68 mm. Bare-hand tracking of the Quest 2 was utilized. The scene was created using Unity (v. 2022.2.7f1) with Oculus Integration (v. 53.0) for hand pose recognition, poke and grabbing interaction, and other functionality.

4.1.4 VR environment

A simple outdoor VR scenery was used for the evaluation (displayed in Fig. 2). Participants found themselves in the middle of a yard (9.5 m in width) surrounded by low (0.25 m) walls, except for the front wall (4 m) which marked the boundary of usable interactable space (4 m at the distance). The view behind the low walls contained a sunset skybox and floor tiles extending towards the infinity.

Virtual hand models from Oculus Integration asset were used, with textures from the package Hafnia Hands (Pohl and Mottelson 2022), which provides hands with skin tones from the six-step range of Fitzpatrick scale (Fitzpatrick 1988). The size of the hand models was automatically scaled according to the user's hand.

4.2 Tasks

4.2.1 Selection task

This task assessed users' performance in hand steering. A cube with a side length of 0.25 m was displayed in front of the user. When touched by the index finger from the front side, the cube started moving to a new location (10 trials in total, ranging from 0.5 to 1.5 m in front of the user, 0 m to 2 m to the sides, and 0.5–2 m above the floor). Users were tasked to follow the cube with the virtual hand and tap its front side every time it stopped moving. The primary metric for assessing user improvement in this study was the difference in completion times between the first and second runs of the selection task.

4.2.2 Docking task

This pick&place task examined performance in grabbing and fine manipulation. Users were required to pick a cube (side 0.1 m) using a grasping gesture and rotate it according to instructions. Then, users had to insert the cube into a plank with a hollow that matched the cube dimensions. Positional (top-down and left-right axes in centimeters) and rotational (roll, pitch, yaw in degrees) displacements were determined for each trial of this task. The task was presented first near the user, followed by variants 1.5 and 2 m at the distance in front of the user, respectively. The average accuracy loss (positional and rotational error) for the 1.5–2 m

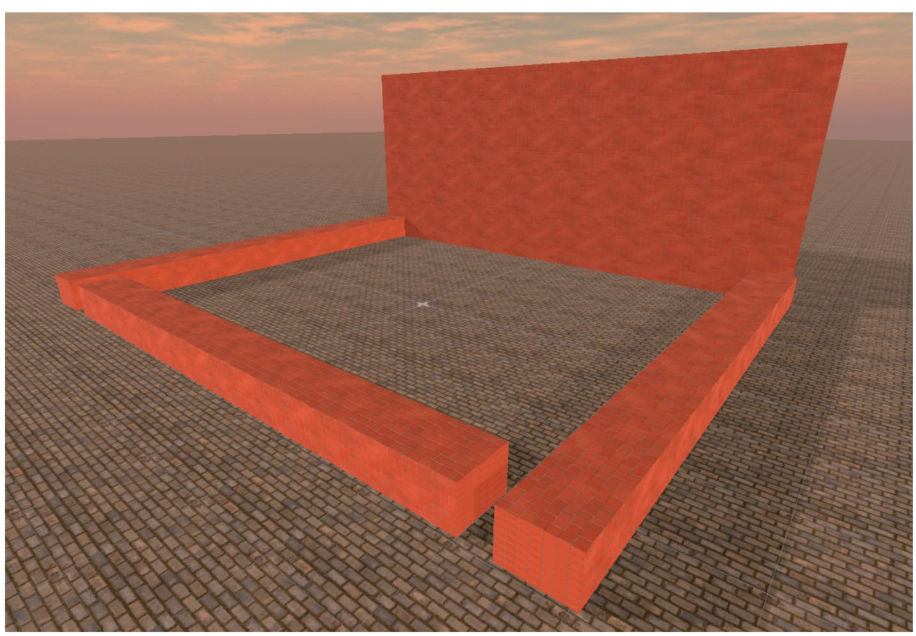

Fig. 2 Overview of the VR scene for the pilot and main study. The participant was positioned in the middle of the space, above the cross mark

task variants was calculated relative to the near-user condition, based on the two best trials out of three per distance.

4.2.3 Keypad task

This task was focused on a consecutive selection at a fixed distance using a button metaphor. Participants were required to enter three five-digit numbers on a numerical keypad (buttons were squares with 2.5cm side lengths). The task was again presented near the user, at 1.5 m, and at 2 m distances. Increases in average completion time for 1.5 and 2 m distances compared to the near-user version were calculated based on the three trials per distance.

4.3 Questionnaires

In terms of embodiment, the sense of ownership (SoO) and sense of agency (SoA) towards the virtual hands were assessed using questionnaires based on (Roth and Latoschik 2020). Specifically, the 'Ownership' and 'Agency' scales were used, with occurrences of the word 'body' replaced by 'hand', and the question 'It felt like the virtual body parts were my body parts' omitted. Cognitive workload was measured using the raw NASA-TLX (Hart and Staveland 1988).

The questionnaires also assessed user affect, derived from the average of responses to questions on whether steering the hands was 'enjoyable', 'interesting', and 'pleasant'. Additionally, usability-related questions evaluated the speed of hand steering ('The speed of the virtual hand moving through the environment was sometimes too fast/slow'), ease of gesture performance ('The gesture that controlled the hand movements was simple to perform'), and ease of steering ('It was easy to control the direction of the virtual hand moving through the environment').

Responses to all questions were recorded on a 7-point Likert scale, ranging from 1 ('Not at all') to 7 ('Completely').

4.4 Procedure

After the motivation and usage of Hand Gliding were explained, participants were handed the HMD with instructions for customization. The experiment was performed while standing up.

Table 1 Mean reduction in accuracy for the docking task (positional and rotational error) and keypad task (percentage increase in completion time, excluding HDS time, and the average increase in number of corrections made in all trials of the task per distance). SDs are in parentheses

Task	1.5 m	2 m
Docking (positional)	0.26 cm (0.61)	1.03 cm (0.71)
Docking (rotational)	0.75° (5.48)	3.90° (6.40)
Keypad (time increase)	45.65% (42.77)	45.52% (46.24)
Keypad (corrections increase)	0.60 (0.97)	0.40 (0.84)

The first stage of the experiment contained training variants of the experimental tasks (the interactables were in peripersonal space, not at a distance), while the experimenter explained them verbally. Then, Hand Gliding was enabled and participants were instructed to practice hand steering for as long as desired until they were confident enough to continue with the procedure.

In the second phase of the experiment, participants were required to use the Hand Gliding technique to interact during the tasks. The interactables were located beyond their arm's reach, and walking was prohibited. The tasks went as follows: selection task, docking task, keypad task, selection task. After the second stage, participants received questionnaires (pen and paper method).

The entire experiment lasted approximately 30 min, while participants spend an average of 16.40 min in VR ($SD = 4.87$).

4.5 Results

4.5.1 Performance

Performance improved between the first and second runs of the selection task, as measured by completion times. Nine participants showed improvement, while one had nearly identical completion times (<1% increase). The mean reduction in completion time was -29.70% ($SD = 14.96$). This difference was statistically significant ($V = 54, p = 0.004$), as determined by the Wilcoxon rank-sum test.

Mean HDSS in the first run of the task was $0.55\ \mathrm{m\,s^{-1}}$ ($SD = 0.41$) and $0.69\ \mathrm{m\,s^{-1}}$ ($SD = 0.47$) in the second run.

4.5.2 Accuracy

Table 1 summarizes the accuracy-related results for the docking and keypad tasks. These values provide an overview of the accuracy loss and increased task completion time when performing the tasks at 1.5–2 m distances using Hand Gliding.

4.5.3 User experience

Questions regarding gesture execution and steering in VR indicated that participants generally found steering the virtual hand easy, with a mean rating of 5.6 out of 7 ($SD = 0.97$). However, responses to the gesture itself were more polarized: five participants rated its ease of execution as high (6 or 7), while the remaining five found it more difficult (rating it 3 or 4).

Participants reported a generally positive affect, with a mean rating of 6.30 ($SD = 0.76$). The perceived steering speed was mostly considered appropriate, with low ratings for both *too slow* (2.56, $SD = 1.33$) and *too fast* (2.67, $SD = 1.22$), suggesting that speed was not a significant usability concern.

Perceived virtual hand ownership was high, with a mean SoO rating of 5.75 ($SD = 0.58$), despite the substantial distortions to the body schema. Similarly, participants reported a strong SoA over the flying hands, with a mean rating of 6.04 ($SD = 0.73$).

Finally, the cognitive workload, evaluated by the NASA-TLX (see Table 2), did not indicate a substantial task difficulty.

4.6 Discussion

The pilot user study demonstrated the feasibility of the proposed method, showing that participants were able to a) utilize Hand Gliding navigation to reach remote targets, and b) complete remotely positioned interaction tasks with reasonable temporal and accuracy loss. Despite half of the participants finding the gesture used for Hand Gliding control difficult to perform, both affect and embodiment remained high.

All participants successfully learned to use the novel interaction technique. Questionnaire results suggest that the mechanisms for controlling steering direction and speed did not present significant obstacles. This is further supported by the selection task results, which indicate that most participants improved their hand-steering accuracy over time.

The primary obstacle to using the method was the employed gesture. Most issues were technical, as the system occasionally failed to register the extended little finger in certain participants or hand positions due to an obstructed camera view during hand tracking. Furthermore, two participants were physiologically unable to perform the gesture correctly. Consequently, we opted for a simpler gesture in the subsequent experiment and eliminated the requirement to maintain the gesture throughout the entire hand-steering process.

Table 2 Results of the NASA-TLX in the pilot study (mean values and SD, on the scale 1-21)

Scale	Pilot study
Mental demand	3.96 (3.93)
Physical demand	5.76 (5.51)
Temporal demand	3.91 (3.71)
Performance	2.57 (2.53)
Effort	4.74 (4.50)
Frustration	2.87 (2.81)

5 Implementations for the main study

5.1 Implemented interaction techniques

This sections lists the compared out-of-reach interaction techniques and details their implementation.

5.1.1 Hand Gliding

Hand Gliding was implemented based on the pilot implementation, with some adjustments that are detailed in Section 3.3.

5.1.2 Laser Gliding

A velocity-to-velocity technique incorporating a raycasting-aided selection of the initial hand destination, 'Laser Gliding', was conceived to counter-balance the raycasting-aided position-to-position technique (HOMER). Analogically, Laser Gliding allows for fast selection of the position of the virtual hand at a distance. Upon raycasting-aided selection, the virtual hand is instantly transported to the distance. The user then has the opportunity to further control the hand with the velocity-to-velocity mapping, or turn the interaction technique off while having the virtual hand at a distance.

5.1.3 Go-Go

The Go-Go interaction technique was implemented closely following the original paper (Poupyrev et al. 1996). A different approach was selected for determining the origin of the interaction space; instead of measuring the hand position relative to the center of the chest, the position of the shoulder was determined in the study. This was done to correct the unequal 'growth' affordances between the left and right sides. By implementing Go-Go as switchable (users could turn the method off while the hand was at a distance) together with implementing the clutching functionality, users did not have to maintain a fully extended arm for interaction at great distances.

5.1.4 HOMER

Our implementation of HOMER has some differences from the original proposal (Bowman and Hodges 1997). Specifically, the virtual hand is only transferred to the position given by the ray-aided selection, but not attached to any object. In a set-up with bare-hand tracking where selection can be done using a variety of gestures for different purposes (e.g., pinching or grabbing has usually a different purpose than poking), attaching an object to the virtual hand would introduce confusion or interaction ambiguity.

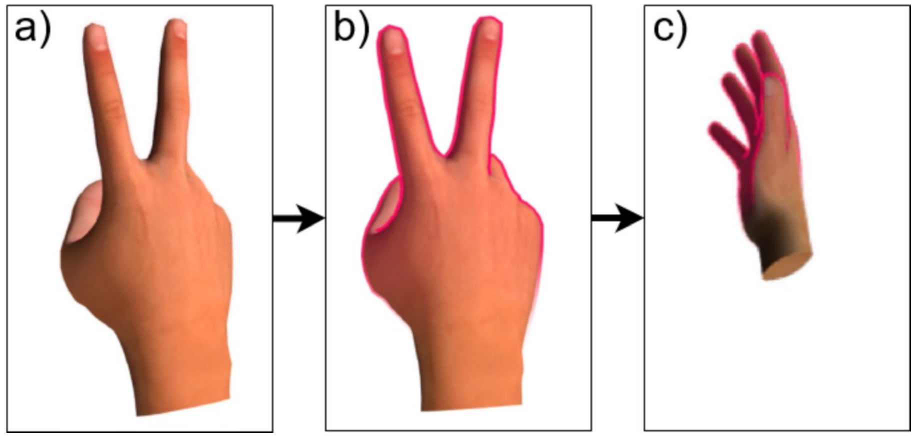

Fig. 3 Activation of the out-of-reach interaction techniques. Users utilized the V-gesture **a** to activate the technique. A pink outline around the hand (middle) indicated an activated out-of-reach interaction technique **b**. Users can now interact beyond the reach of their arms **c**. In the case that the raycasting-aided technique was activated, the user obtains the ray for choosing a new hand location (see Fig. 6)

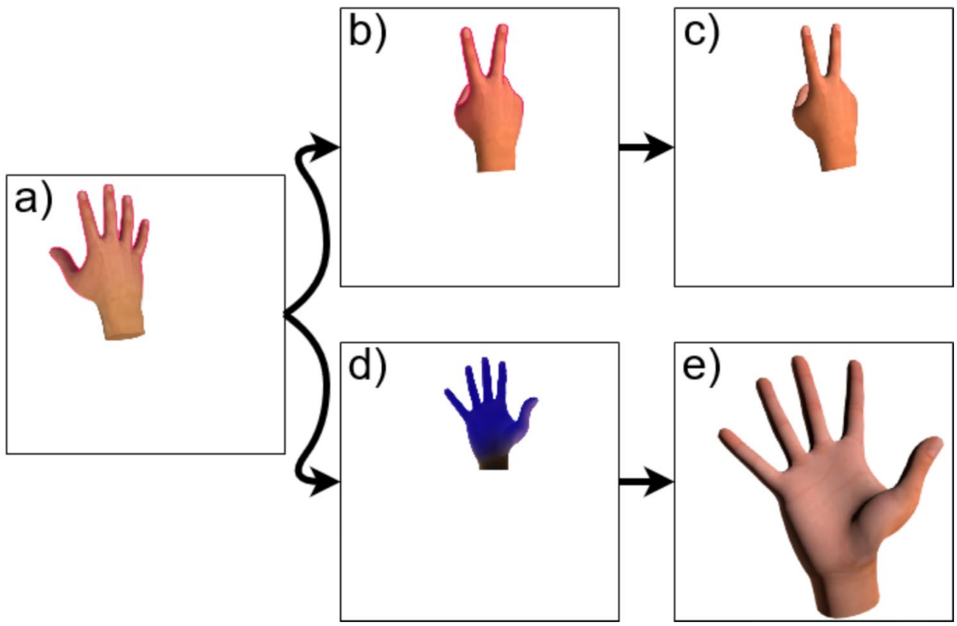

Fig. 4 Deactivation of the interaction techniques. While in distance **a**, the technique can be deactivated by the V-gesture **b** which results in the hand staying at the distant location while the technique is deactivated **c**. By using the palm gesture **d**, the technique is deactivated, returning the hand to its congruency with the physical hand **e**

Analogically, returning the hand back to congruency with its physical counterpart is done upon explicit action (gesture), rather than by releasing the held object as done in the original HOMER. As in our implementation of Go-Go, the origin of the interaction space was set at the shoulder of the user, instead of the torso.

5.2 Control gestures and modes

All techniques were controlled using a common set of hand gestures. A sound effect was played upon each successfully recognized gesture, providing immediate auditory feedback. Additionally, when a switchable state was activated, a colorful outline was rendered around the hand to inform the user.

The techniques were implemented as switchable modes, requiring activation via a specific gesture (a V-sign, as shown in Fig. 3). To regain the precision of close-body interactions, users could deactivate the technique while their virtual hand remained at a distance by performing the same gesture. In that case, deactivation did not alter the hand's position (see Fig. 4 for details). When an out-of-reach interaction technique was active, a pink outline was rendered around the hand for visual feedback.

5.2.1 Turning the methods on and off

The amplified hand interaction with one of the four implemented out-of-reach interaction techniques was turned on by performing the V-gesture shown in Fig. 3. The pink outline around the hand indicated that either velocity-to-velocity control was active (in Hand Gliding) or that extending the arm would increase the reach (in Go-Go). If one of the raycasting-aided techniques was selected, the V-gesture initiated the raycasting step. In all cases, performing the V-gesture while the hand was outlined in red deactivated

Fig. 5 The gesture controlling clutching. After the users performed this gesture, the virtual hand position was not affected by changes in the physical hand position, until the gesture was released. The added blue outline indicates that clutching is activated

the interaction technique, without resetting the hand position (see Fig. 4).

5.2.2 Raycasting-aided methods

In raycasting-aided methods, performing the V-gesture generated a laser-like ray. This ray aligned with a vector determined by the position of the knuckle at the center of the middle finger and its fingertip. The initial step in HDS was performed by dwelling at the intersection of the ray and the target object (see Fig. 6). After repositioning, the interaction technique remained active for further use.

The virtual hand was repositioned 20 cm in front of the target (on the path of the ray). The selection was performed if the standard deviation of the ray-target intersection points over the last 750 ms remained within 7.5 cm. These thresholds were arbitrarily selected to ensure easy HDS towards the objects in the experimental tasks. The raycasting-aided HDS method was implemented uniformly across both the HOMER and Laser Gliding techniques.

Users had an opportunity to further influence their physical-to-virtual hand configuration with raycasting-aided HDS. Firstly by moving the hand farther or closer to the body, and secondly by rotating the physical hand position at an angle before confirming the ray selection (participants were made aware of this before interacting with raycasting-aided methods in the experiment).

5.2.3 Clutching

Users could also use clutching with all interaction methods. Clutching enables the temporary suspension of the linkage between the physical hand position and the virtual hand position, allowing for independent control of the physical hand. When the user performed the clutching gesture (clenching the fist, Fig. 5, right), the virtual hand would not move (it only rotated) according to the physical hand movements. The activated clutching added a blue outline to the pink outline rendered around the hand (users could use clutching only when an interaction technique was on, indicated by the pink outline).

5.2.4 Resetting the position

By opening and rotating the hand with a palm facing the HMD (Fig. 4d), the virtual hand returned to congruency with its physical counterpart, and the interaction method was turned off (Fig. 6).

5.3 Positional data filtering

Natural hand tremor and limited human pointing precision are common limitations of interaction at a distance (König et al. 2009), apparent when the hand movements are amplified. This issue arises with techniques such as HOMER and Go-Go, as well as with raycasting, when the end of the ray is positioned to a large distance. To mitigate, we implemented the option to switch from high CD gain to a 1:1 ratio (by disabling the technique) when remote interaction is required. Additionally, 1€ filter (Casiez et al. 2012) was employed in our implementations of HOMER and Go-Go. This filtering approach has been successfully deployed in previous works in VR interaction (Baloup et al. 2019).

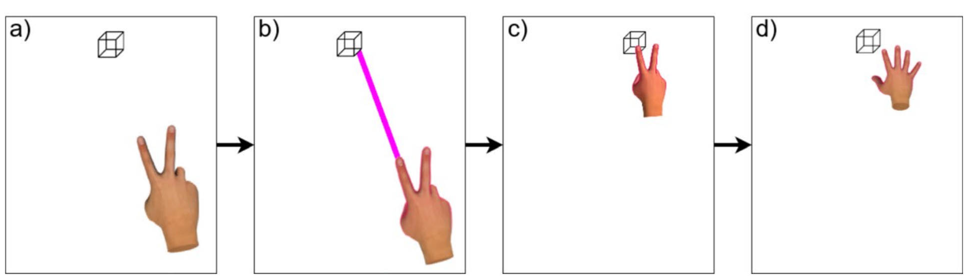

Fig. 6 This image illustrates hand-based out-of-reach interaction using raycasting-aided hand positioning (HOMER and Laser Gliding). The process begins with a gesture **a** that activates a guiding ray **b**. Then, after dwelling on an object, the hand is moved in front of the intersection of the ray with the selected object **c**. Finally, users can interact with objects in the scene with gestures and interaction technique-specific amplification of hand movements **d**. The extent of the hand movements at the distance is adjusted according to the chosen interaction method

5.4 Positioning of the interactable elements

We adopted the 'virtual cubit' (Poupyrev et al. 1998) (further referred to as '*vc*') distance unit that represents the reach of the user's extended arm (we measured *vc* as the distance between the shoulder and the center of the hand). As comfortable hand movement tends to be described by arcs rather than following straight lines (Sengupta and Das 2000), all interactable elements were positioned on a hypothetical sphere multiples of *vc*s far from the user's shoulder and rotated towards the user. Positioning can thus be described in terms of vertical and horizontal angles and the distance from the user (Poupyrev et al. 1998).

6 Main study: comparison of the techniques

The main study compared Hand Gliding and Laser Gliding–velocity-to-velocity interaction methods–with position-to-position techniques (Go-Go and HOMER) for out-of-reach interaction. In each pair, one technique employed raycasting to aid in HDS (Laser Gliding, HOMER), while the other relied solely on hand-based positioning (Hand Gliding, Go-Go).

6.1 Participants and apparatus

A total of 25 participants (12 female, 13 male) took part in the main study, following recommendations for VR selection and manipulation studies from Bergström et al. (2021). The mean age was 32 years ($SD = 6.39$), and reported VR experience is visualized in Fig. 7. One participant was left-handed, while the remaining 24 were right-handed.

The same VR HMD (Meta Quest 2), VR application, and virtual environment as in the pilot study were used (see Section 4 for details).

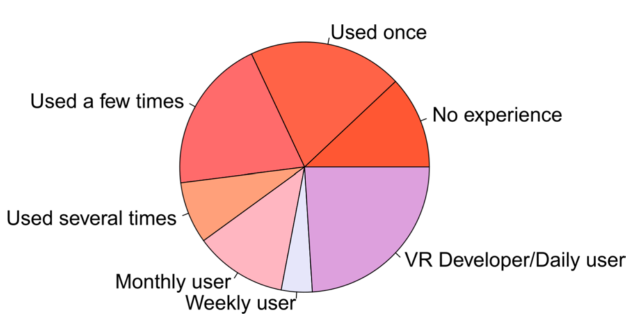

Fig. 7 Demographics of the sample: reported VR experience prior to the experiment

6.2 Study design

This study employed a within-subject design with a single independent variable: *interaction method*. Participants performed a series of tasks using each of the four interaction methods and answered questionnaire after each of the four conditions. Task interactables were positioned at various angles and distances, measured in multiples of vc from the user's shoulder position. This normalization accounted for individual differences in arm length.

The experiment was conducted in a controlled environment, allowing the measurement of the user's shoulder position. This measurement was used as the center of the coordinate system for the 'growth' function in Go-Go and HOMER.

The order of the methods was counterbalanced, but non-raycasting methods always preceded their raycasting-enhanced counterparts. Specifically, the sequence was either Go-Go, HOMER, Hand Gliding, Laser Gliding; or Hand Gliding, Laser Gliding, Go-Go, HOMER. This approach was designed to minimize cognitive overload. Participants needed to learn multiple steps for effective control of the techniques, such as handling gestures, deciding whether to deactivate the interaction technique at a distance, determining whether to reactivate the technique or reset the hand position, and when to use clutching. By introducing the non-raycasting method first, we distributed the learning process across more stages of the experiment. This ensured that participants became proficient with the non-raycasting method before introducing the more complex raycasting version.

6.3 Measures

6.3.1 Completion time and selection metrics

Each task had either one main metric–HDS time (in cases where it corresponded to selection time)–or two associated metrics (HDS time and task-specific selection time) used for statistical analysis. When completion time could be decomposed into HDS and task-specific selection at the distant target (as in the keypad task), these metrics were analyzed separately.

6.3.2 Hand destination selection speed

Values of HDSS (see Section 3.2) were computed per type of HDS based on the task (rapid HDS, keypad HDS, translation HDS). While tightly linked to the main temporal metric, HDSS values are presented separately for comparability with other studies. HDSS facilitates the analysis of movements across different extents, either combined or separately. Each type of HDSS was further categorized by interaction distance from the user ($2vc$, $3vc$, or $4vc$) and movement type (horizontal, vertical, and depth-wise movements). Combined movement patterns were excluded from this breakdown. The number of horizontal, vertical, and depth-wise movements per task type is provided in the task descriptions.

6.3.3 User pose

User pose during keypad interaction was analyzed based on the average physical hand position. Vertical and lateral positions were measured relative to the user's shoulder, while depth-wise position was measured relative to the center of the VR scene, where the user was initially located. Lateral displacement was computed relative to the shoulder, with negative values indicating displacement toward the body's center and positive values indicating outward displacement.

Hand positioning data served as an indicator of physical comfort. Since interacting with targets that are too high or too far can cause strain, lower values were interpreted as preferable. While interactions that are too low or too close to the body could also be uncomfortable, this issue did not arise with the tested out-of-reach interaction techniques.

6.3.4 Clutching and reactivation events

The frequency of clutching and the number of reactivations of the method were logged for descriptive statistical analysis.

6.3.5 Subjective measures

Subjective responses were collected on:

- Perceived SoO and SoA (Roth and Latoschik 2020)
- Rating of Perceived Exertion (RPE) (Borg 1982)
- Cognitive workload (NASA-TLX) (Hart and Staveland 1988)

Cognitive workload was assessed using a subset of the raw NASA-TLX (mental and physical demand, effort, and frustration).

6.3.6 Statistical testing

Statistical testing of differences was performed with the Friedman test (with the interaction method as the within-subject factor). Our reports contain Kendall's W as an effect size metric. Post-hoc pair-wise comparisons were performed using Wilcoxon tests while adjusting for multiple comparisons using the Holm-Bonferroni method. Data visualization using bar graphs contains error bars based on 95% confidence intervals.

To reduce the influence of extreme values, we excluded outliers from the dataset using a standard 1.5 $\times$ IQR rule: values falling below $Q1 - 1.5 \times \mathrm{IQR}$ or above $Q3 + 1.5 \times \mathrm{IQR}$ were removed. This was applied to HDS and HDSS metrics independently for each condition. While the threshold is conventional rather than data-driven, it offers a reasonable compromise between robustness and sensitivity in the context of human performance variability.

6.4 Tasks

6.4.1 Task design

Experimental tasks aimed to investigate various types of interaction, with emphasis on selection and translation. Rotation was not investigated, as the interaction methods did not amplify rotational movement.

The positioning of task interactables was aligned with the virtual hand 'growth' in position-to-position interaction methods. Both the interactables and the shifted virtual hands were positioned relative to the user's shoulder, which served as the origin point. Interactables were placed at distances defined as multiples of vc and dynamically scaled based on the distance between the user's eyes and the interactable (with the base size defined at a one-meter distance). This setup ensured uniform experimental conditions, independent of individual arm length.

When reporting on horizontal or vertical movements in a task, users performed movements constrained to a fixed depth distance, following an arc. For left-handed participants, the task positioning was adjusted by centering it at the left shoulder and mirroring the x-axis.

6.4.2 Rapid selection task

The rapid selection task (Fig.8) examined the speed of consecutive selection of randomly positioned targets. The goal of this task was to tap a user-facing side of a small cube (base side length 10 cm) at its location. After tapping the cube, it was instantly teleported to a new location (a flash of an arrow from the last cube position to its current position was displayed briefly to make sure participants knew about the new location instantly).

This task had 19 trials. Participants tapped the cube at the depth-wise distance of 2, 3, or 4 vc; at $0°$ or $\pm 30°$ horizontally; and $0°$, $\pm 15°$, or $\pm 30°$ vertically. The sequence of cube positions was prepared to require the participants to transition their hand positions in a horizontal way ($4\times$), vertical way ($5\times$), depth-wise ($2\times$), or in a direction combining the previous ($8\times$). The transitions are detailed in Table 3.

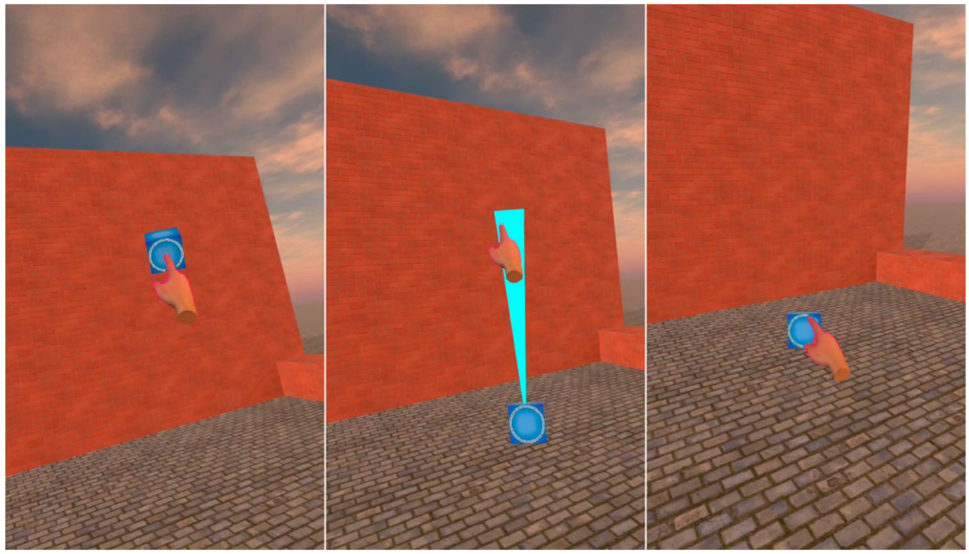

Fig. 8 Rapid selection task: The user is required to poke the cube in each location, which is changed instantaneously after the poke

Table 3 Positioning of the interactable cube in the rapid selection task. The horizontal axis was mirrored for left-handed participants

Horizontal	Vertical	Depth-wise
−30°	−30°	2*vc*
30°	−30°	2*vc*
30°	15°	2*vc*
−30°	15°	2*vc*
−30°	−30°	2*vc*
0°	0°	2*vc*
0°	0°	4*vc*
30°	15°	4*vc*
30°	−30°	4*vc*
−30°	−30°	4*vc*
−30°	15°	4*vc*
30°	15°	4*vc*
−30°	−30°	4*vc*
−30°	−30°	2*vc*
−30°	15°	2*vc*
30°	−30°	2*vc*
30°	15°	3*vc*
−30°	15°	2*vc*
−30°	−30°	3*vc*
30°	−30°	2*vc*

The metric from this task is the rapid HDS time (the time between the appearance of the next target, until the target was hit; the first trial was not taken into account).

6.4.3 Keypad task

The keypad task evaluated the speed of consecutive selections of small targets at a fixed distance. The goal was to enter a number on a virtual keypad (Fig. 9) by poking the buttons, each with a base side length of 2.5 cm. In each trial, a number was randomly selected from the set 159, 951, 753, 357. This selection ensured that participants always performed movements of the same extent, incorporating both horizontal and vertical displacement, thereby maintaining consistent conditions across trials.

Fig. 9 Keypad task: The user is required to press the buttons corresponding to the target number on the remotely positioned keypad

If an error was made, participants had to delete the incorrect digit by pressing the 'X' button. Upon successfully typing the number, the keypad reappeared at a new location, and the interaction technique was reset. Specifically, the virtual hand was returned to congruency with the physical hand, and the interaction technique was deactivated before the next trial.

This task had 9 trials; at the depth-wise distance of 2, 3, or 4 *vc* (each three times). Positioning either 0°, ± 30°, or ± 45° horizontally, while the vertical positioning was not manipulated (i.e., placed at the vertical position of the user's shoulder). Details on the sequence of trials are provided in Table 4.

The metrics from this task were the keypad HDS time (time from the beginning of the trial until the press of the first button) and the keypad selection time (time from the pressing of the first button until pressing the last button of the number). Keypad HDS is a special case of HDS when the virtual and physical hands are in congruency at the beginning of the trial. Additionally, hand position during the selection process was monitored, and the average depth-wise positioning and hand height during the selection were evaluated.

Table 4 Positioning of the interactable in the keypad task. The horizontal axis was mirrored for left-handed participants

Horizontal	Depth-wise
45°	2*vc*
−30°	4*vc*
0°	3*vc*
45°	4*vc*
45°	3*vc*
0°	4*vc*
−30°	2*vc*
−30°	3*vc*
0°	2*vc*

6.4.4 Translation task

The translation task (see Fig.6) involved translating objects beyond the limits of arm's reach. Users were required to perform a pinch gesture to select an object, move it using amplified hand movements, and release it into a predefined target area.

The objective was to pick up a small cube (base side length: 10 cm) and place it inside a larger wireframe cube (base side length: 15 cm). Once the interactable cube entered the target cube, its texture turned green to indicate that it could be released. Both cubes were dynamically scaled based on their distance from the user. However, if the target cube was positioned closer than the interactable cube, its size was adjusted to remain 1.5 times larger than the interactable one.

This task had 17 trials; at the depth-wise distance of 2, 3, or 4 *vc*. Positioning either 0° or ± 30° horizontally, 0° or ± 15° vertically. Positioning of the interactable and the target cubes required users to move hands horizontally 6×, vertically 4×, depthwise 2×, and a combination of the above 5×. Details on task positioning are present in Table 5.

The metrics from this task were the pinch selection time (time from the beginning of the trial under the interactable cube was pinched) and the translation HDS time (computed from the pinch-taking of the cube until releasing it to the target cube). HDS was not computed from the selection part of this task, for the reason that the interactable cube was often positioned at the last trial's location of the target cube. Selection thus comprised mostly correctly performing the gesture while aiming at the distant target, not of moving the hand toward the target (i.e., as the hand was already positioned near the interactable, no HDS had to be performed).

6.4.5 Training scenes

Participants completed two training scenes before the experimental tasks. The first scene had no specific objectives and allowed participants to familiarize themselves

Table 5 Positioning of the interactable cube and the destination cube in the translation task (H stands for horizontal position, V for vertical, D for depth-wise. The horizontal axis was mirrored for left-handed participants

Interactable				Destination		
H	V	D		H	V	D
30°	0°	2*vc*	→	−30°	0°	2*vc*
−30°	0°	2*vc*	→	30°	0°	2*vc*
30°	0°	3*vc*	→	−30°	0°	3*vc*
−30°	0°	3*vc*	→	30	0°	3*vc*
30°	0°	4*vc*	→	−30°	0°	4*vc*
−30°	0°	4*vc*	→	30°	0°	4*vc*
0°	0°	4*vc*	→	0°	0°	2*vc*
0°	0°	2*vc*	→	0°	0°	4*vc*
0°	15°	4*vc*	→	0°	−15°	4*vc*
0°	−15°	4*vc*	→	0°	15°	4*vc*
30°	15°	3*vc*	→	30°	−15°	3*vc*
−30°	−15°	2*vc*	→	−30°	15°	2*vc*
−30°	15°	2*vc*	→	30°	−15°	2*vc*
30°	−15°	2*vc*	→	−30°	15°	2*vc*
−30°	15°	2*vc*	→	30°	−15°	3*vc*
30°	−15°	2*vc*	→	−30°	−15°	4*vc*
−30°	−15°	4*vc*	→	−30°	15	2*vc*

with the interaction technique and its controls. Gestures for controlling the interaction were displayed on a virtual wall within the VR environment.

The second training scene required participants to poke semi-translucent virtual spheres appearing at increasing distances (0.6, 2, 3, and 4 vc) and varying sizes. This 'bubble popping' task ensured that participants could effectively control the technique. Once all bubbles at increasing distances were popped, smaller bubbles (2.25 cm diameter) at $3vc$ were presented to demonstrate that deactivating the hand interaction technique at a distance restored precise hand control. The scene concluded with bubbles appearing near the participant's body to confirm their ability to correctly perform the reset gesture.

The training sessions were guided by the experimenter to ensure proper understanding and technique usage.

6.5 Procedure

At the beginning of the session, participants signed a consent form and completed a pre-experiment questionnaire assessing their dominant hand (using a shortened version of the Edinburgh Handedness Inventory from Oldfield (1971)) and their VR experience. The VR experience rating was based on a 7-point scale with the following categories: no experience, used once, used a few times, used several times, monthly user, weekly user, and VR developer/daily user (Bergström et al. 2021).

Participants were then briefed on the structure and purpose of the experiment. The control gestures for the interaction techniques and the experimental tasks were explained. They were also encouraged to maximize comfort during the experiment, such as by using the clutching feature. During the VR portions, the experimenter monitored progress and provided guidance, particularly during the introductory training scenes.

The following procedure was repeated for each experimental phase (i.e., for each interaction method). Before each phase, participants were given instructions specific to the corresponding interaction technique. Participants were seated in a swivel chair with armrests, allowing rotation but restricting translation and excessive leaning.

At the beginning of each VR phase, participants selected a hand skin tone to enhance embodiment (Argelaguet et al. 2016). Next, their arm and hand properties were calibrated by recording the shoulder position and vc length. To ensure accuracy, participants extended their arm while the experimenter verified its position, as the HMD could interfere with the user's ability to estimate a fully extended pose. Positional coordinates were continuously recorded until the last 2 s of data had a standard deviation below 2 cm.

The experimental tasks were then conducted in the following order: the translation task, the keypad task, and the rapid selection task. After completing the tasks, participants filled out questionnaires, including RPE, the body ownership questionnaire (see Section 4.3 for details), and the NASA-TLX. At the end of the experiment, participants were asked about their preferred interaction technique ('Which technique did you like the most?') and had the opportunity to provide additional comments.

The entire experiment lasted between 60 and 90 min, with participants spending an average of 54.90 min in VR ($SD = 10.20$).

7 Results

7.1 Performance

Performance results are analyzed in terms of task completion times (all present in Table 6). In addition, the HDSS values are provided in a summary table Table 7. Figure 10 provides a visual overview of the results.

7.1.1 Rapid selection task

Rapid selection of randomly positioned targets was the fastest with position-to-position methods. Friedman test revealed a significant main effect of the interaction method ($\chi^2(3) = 20.60, W = 0.27$). In pairwise comparisons, Go-Go and HOMER were both statistically significantly faster than Hand Gliding. Details on completion times, post-hoc pairwise Wilcoxon test, and their effect sizes are present in Table 6.

Compared to HOMER, Go-Go yielded high speeds in depth-wise movements (see Fig. 11). Go-Go was the most efficient method for this task.

7.1.2 Keypad task

Task times for multiple selections at a fixed distance (keypad task) were divided into two components: the time required to reach the interactable (keypad HDS time) and the time required to perform the selections (selection time).

Friedman test did not reveal a significant main effect of the interaction method ($\chi^2(3) = 0.07, p = 0.99, W < 0.001$) on the HDS time. The values were comparable, while Laser Gliding yielded the shortest HDS time. Friedman test did reveal a significant main effect of the interaction method ($\chi^2(3) = 8.14, p = 0.04, W = 0.11$) on the selection times in the keypad task. While Laser Gliding yielded the

Table 6 Completion times and pairwise comparisons for all tasks per interaction method. The third column contains the mean completion times (seconds, SD in parentheses), and the other columns represent the Wilcoxon pairwise comparison with corrected p-values and effect size in parentheses. Effect sizes are reported as *r*, calculated as $r = \frac{Z}{\sqrt{N}}$, following Cohen's conventions. The shortest completion times and significant p-values ($p < 0.05$) are highlighted with bold italics

Task	Interaction techniques (completion time and *p*-values of differences)				
Rapid HDS		**Time (s)**	**HOMER**	**Hand Gliding**	**Laser Gliding**
	Go-Go	**46.16 (24.46)**	0.40 (0.18)	**< 0.001 (0.78)**	**0.004 (0.63)**
	HOMER	50.91 (28.46)	-	*0.002 (0.66)*	**0.06 (0.46)**
	Hand Gliding	80.27 (47.81)	–	–	**0.06 (0.45)**
	Laser Gliding	63.21 (22.21)	–	–	–
Keypad HDS		**Time (s)**	**HOMER**	**Hand Gliding**	**Laser Gliding**
	Go-Go	54.64 (23.48)	1 (0.06)	1 (0.04)	1 (0.10)
	HOMER	53.02 (21.06)	–	1 (0.14)	1 (0.06)
	Hand Gliding	58.90 (32.56)	–	–	0.76 (0.31)
	Laser Gliding	**51.21 (17.33)**	–	–	–
Keypad Selection		**Time (s)**	**HOMER**	**Hand Gliding**	**Laser Gliding**
	Go-Go	34.78 (16.89)	0.79 (0.10)	0.66 (0.25)	0.29 (0.38)
	HOMER	39.87 (32.17)	–	0.79 (0.18)	0.40 (0.33)
	Hand Gliding	41.35 (21.90)	–	–	**0.003 (0.65)**
	Laser Gliding	**26.85 (10.49)**	–	–	–
Pinch Selection		**Time (s)**	**HOMER**	**Hand Gliding**	**Laser Gliding**
	Go-Go	52.21 (22.65)	**< 0.001 (0.87)**	0.96 (0.01)	**0.001 (0.69)**
	HOMER	**22.97 (7.61)**	–	**< 0.001 (0.82)**	**0.03 (0.49)**
	Hand Gliding	54.68 (30.98)	–	–	**0.004 (0.61)**
	Laser Gliding	32.07 (20.86)	–	–	–
Translation HDS		**Time (s)**	**HOMER**	**Hand Gliding**	**Laser Gliding**
	Go-Go	210.46 (95.28)	**< 0.001 (0.87)**	0.07 (0.08)	**< 0.001 (0.80)**
	HOMER	**108.85 (46.87)**	–	**< 0.001 (0.69)**	0.15 (0.36)
	Hand Gliding	199.91 (90.91)	–	–	**< 0.001 (0.82)**
	Laser Gliding	132.98 (54.65)	–	–	

Table 7 Mean HDSS ($\mathrm{m\,s^{-1}}$), per type

Method	Rapid HDS	Keypad HDS	Translation HDS
Go-Go	**0.59 (0.18)**	0.43 (0.15)	0.12 (0.04)
HOMER	0.54 (0.12)	0.40 (0.11)	**0.22 (0.06)**
H. Gliding	0.35 (0.11)	0.35 (0.14)	0.14 (0.05)
L. Gliding	0.47 (0.15)	**0.44 (0.12)**	0.21 (0.07)

shortest times, it was statistically significantly lower only when compared to Hand Gliding (see Table 6).

From the breakdown according to the interaction distance (Fig. 12) it is clear that Hand Gliding hindered the positioning of the hand to the greatest distance ($4vc$), which was not the case with the remaining methods.

7.1.3 Translation task

In the first part of the translation task trial, pinch selection was performed most quickly with HOMER. A Friedman test revealed a significant main effect of the interaction method ($\chi^2(3) = 38.40, p < 0.001, W = 0.51$). The subsequent translation was also fastest with HOMER, with another Friedman test confirming a significant main effect of the interaction method ($\chi^2(3) = 37.00, p < 0.001, W = 0.49$); see Table 6.

Depth-wise movements, which are highly scaled-up in Go-Go, become more challenging to aim precisely when target selection demands accuracy. Although this scaling proved advantageous for rapid selection tasks, HOMER delivered faster speeds for gesture-based selection, translation, and object release (see Fig. 13).

7.1.4 Interaction speed

Overview of HDSS per task and method are provided in Table 7, while the breakdown of speeds according to the interaction distance from the user or movement types is visualized in Figs. 11, 12, and 13.

Average speeds achieved by participants with different levels of previous VR experience are visualized in Fig. 14. These values are interesting from the point of view of future study designs.

7.2 Usage characteristics

7.2.1 Hand position

Results showing the average hand positions per method are present in Table 8. The differences were statistically significant in the vertical ($\chi^2(3) = 46.90, p < 0.001, W = 0.63$) and the depth-wise ($\chi^2(3) = 29.60, p < 0.001, W = 0.40$) positions, but not in the lateral displacement.

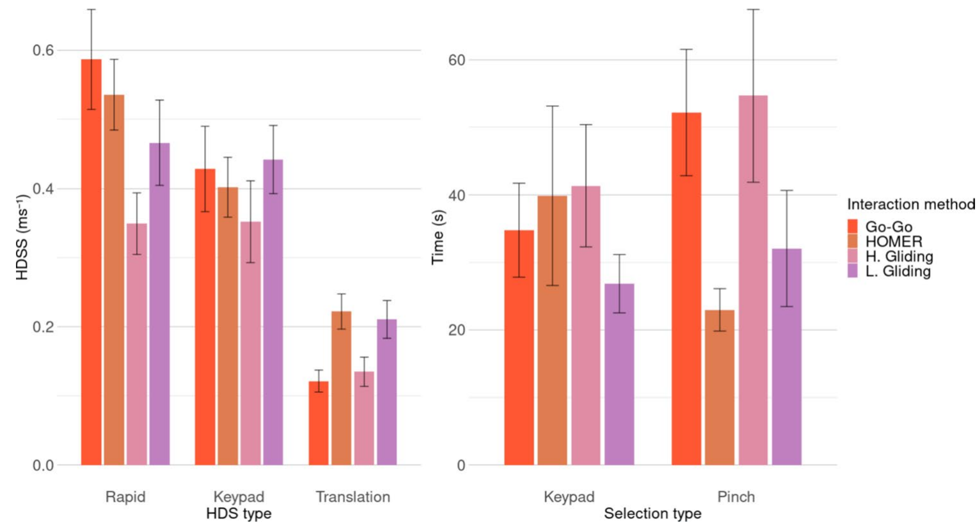

Fig. 10 Results from the comparison of interaction methods per metric. Left: HDSS is shown for the HDS-based metrics (higher speed is better). Right: Remaining selection metrics are represented by selection time (lower time is better). Error bars represent the 95% confidence intervals

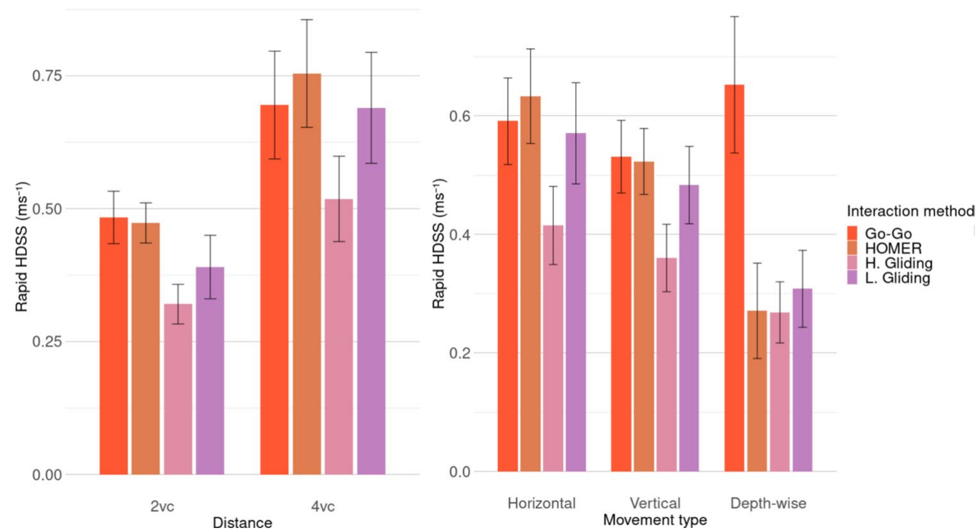

Fig. 11 Rapid selection task: HDSS by interaction distance from the user (left) and by movement type–horizontal, vertical, and depth-wise (right)

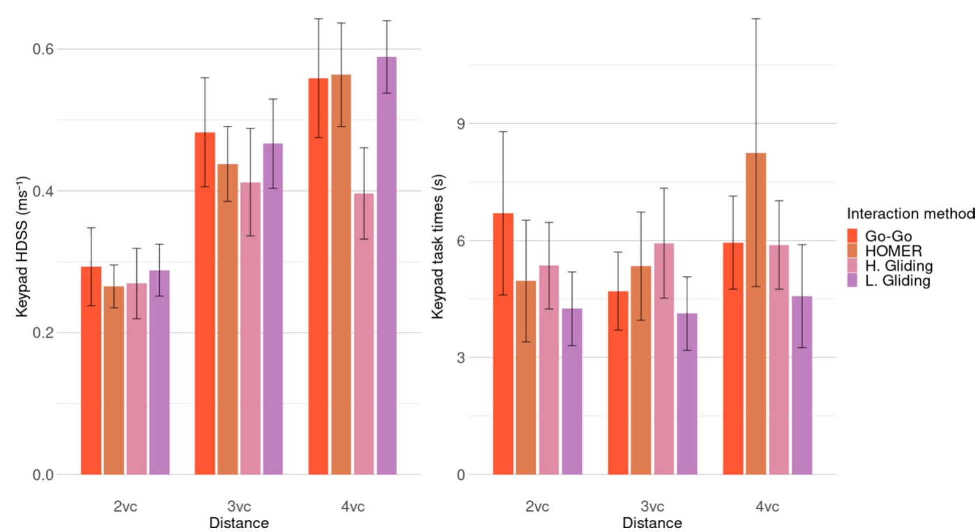

Fig. 12 Keypad task by interaction distance from the user. Left: Keypad HDSS (higher speed is better). Right: Keypad selection times (lower time is better)

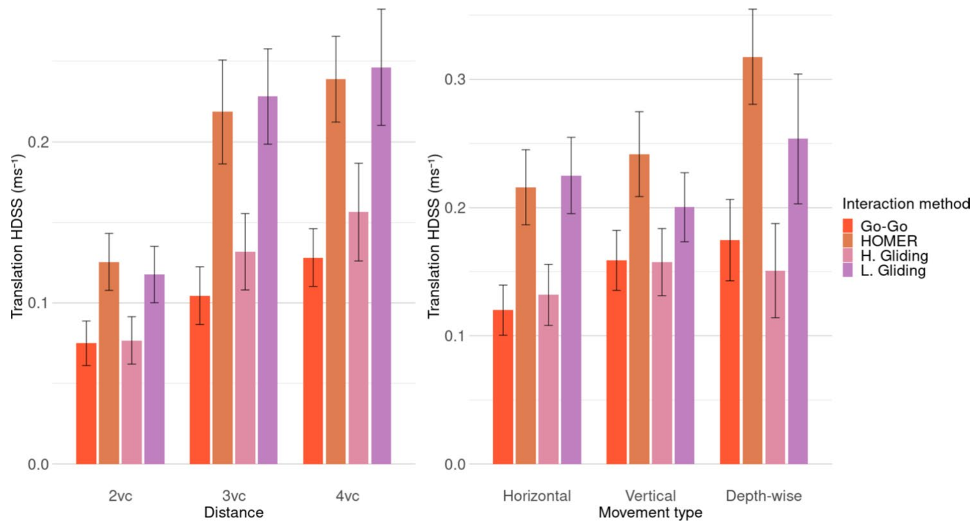

Fig. 13 Translation task: Translation HDSS by interaction distance from the user (left) and by movement type–horizontal, vertical, and depth-wise (right)

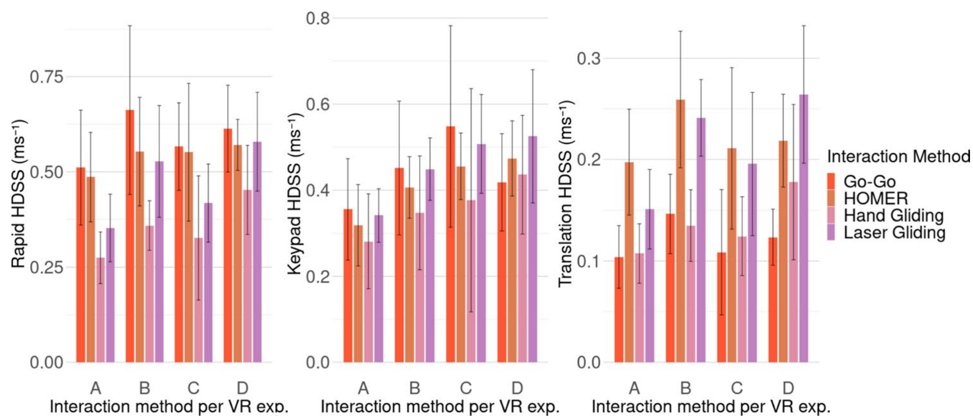

Fig. 14 Mean HDSS across participants with different levels of reported VR experience (**A**: No experience or used VR once before, **B**: Used a few or several times, **C**: Monthly to weekly users, **D**: Daily users and VR developers; see Fig. 7 for participant distribution across categories)

Table 8 Mean vertical, depth-wise, and lateral position of the hands in each task of the experiment (in cm). In the lateral position, negative values represent displacement towards the center of the body (relative to the shoulder) and vice versa, to compensate for the differences between left- and right-handed users

	Vertical pos.	Depth-wise pos.	Lateral pos.
Go-Go	2.3 (4.0)	32.3 (11.1)	−2.9 (3.4)
HOMER	−6.3 (3.6)	***18.9 (9.9)***	−4.2 (5.1)
H. Gliding	−4.4 (5.5)	34.2 (12.5)	−5.3 (4.0)
L. Gliding	**−6.5 (4.2)**	21.6 (7.7)	-5.0 (6.0)

Table 9 Mean reactivations of an interaction method during the session, mean usage of clutching (number of usages), and the percentage of the keypad task trials when the out-of-reach interaction technique was disabled

	Activations	Clutching	Disablements
Go-Go	12.72 (6.34)	5.76 (10.87)	12% (22.89)
HOMER	13.76 (3.76)	2.6 (2.84)	19.11% (32.64)
H. Gliding	20.28 (8.12)	11.56 (11.82)	12% (27.39)
L. Gliding	15.36 (5.13)	2.88 (4.96)	12% (27.76)

In the case of vertical displacement, Go-Go was statistically significantly worse than all the remaining methods ($p < 0.001$ and effect sizes in the range $0.85 < r < 0.87$ in all cases). In the case of depth-wise displacement, Laser Gliding was better than Go-Go ($p = 0.003, r = 0.63$). Additionally, HOMER was better than Go-Go, and HOMER and Laser Gliding were better than Hand Gliding (all with $p < 0.001, 0.73 < r < 0.76$).

7.2.2 Reactivations, clutching, and technique disablement

Mean sums of the number of reactivations of the method, clutching usage, and technique disablements at a distance are provided in Table 9. No statistically significant differences were found in any of these metrics. Hand Gliding required the highest number of both reactivations and clutching. Participants mostly chose not to disable the movement amplification when interacting at a distance, while choosing to disable it most often with HOMER.

7.3 Subjective measures

7.3.1 Perceived embodiment

Perceived virtual hand ownership and agency were investigated with each interaction method (see Table 10). Friedman test did not reveal a statistically significant effect of the interaction method on the perceived SoA ($\chi^2(3) = 6.75, p = 0.08, W = 0.09$), but an effect on the SoO was found ($\chi^2(3) = 10.8, p = 0.01, W = 0.14$). The velocity-to-velocity methods led to a greater reduction in body ownership, while the raycasting-aided methods allowed for stronger body ownership. The only pairwise significant difference was between HOMER and Hand Gliding ($p = 0.005, r = 0.70$). Body ownership strongly followed the perceived agency over the hand movement (Spearman correlation: $r = 0.78, p < 0.001$).

7.3.2 Satisfaction and preferences

Preferred interaction techniques as determined by post-experimental participant interviews are shown in Fig. 15.

There were no significant differences in RPEs between the methods. The results from Friedman test indicate that the methods are not equal ($\chi^2(3) = 10.10, p = 0.02, W = 0.13$), but the pairwise comparisons did not survive the correction with the borderline exception of Hand Gliding vs Laser Gliding ($p = 0.046, r = 0.54$). RPEs, transformed using z-scoring to account for inter-subject variability, are presented in Table 11.

The descriptives for NASA-TLX results are present in Table 12. Friedman test found a significant main effect of the interaction method on mental demand ($\chi^2(3) = 13.60, p = 0.004, W = 0.18$), physical demand (($\chi^2(3) = 13.80, p = 0.003, W = 0.18$), and effort ($\chi^2(3) = 16.40, p < 0.001, W = 0.22$).

In terms of mental demand, HOMER was statistically significantly less demanding than Hand Gliding ($p = 0.02, r = 0.60$). In terms of physical demand, HOMER was less demanding than Go-Go ($p = 0.01, r = 0.64$) and Hand Gliding ($p = 0.04, r = 0.52$), and Laser Gliding was less demanding than Go-Go ($p = 0.04, r = 0.49$) and Hand Gliding ($p = 0.02, r = 0.57$). In terms of effort, Hand Gliding required more effort than Laser Gliding ($p = 0.01, r = 0.67$) and HOMER ($p = 0.03, r = 0.57$).

Table 10 Sense of embodiment: Mean results for the SoO and SoA (scale 1-7)

	SoO	SoA
Go-Go	5.46 (1.15)	5.90 (0.94)
HOMER	**5.65 (0.98)**	**5.93 (1.01)**
Hand Gliding	4.98 (1.00)	5.46 (1.19)
Laser Gliding	5.38 (0.92)	5.87 (0.82)

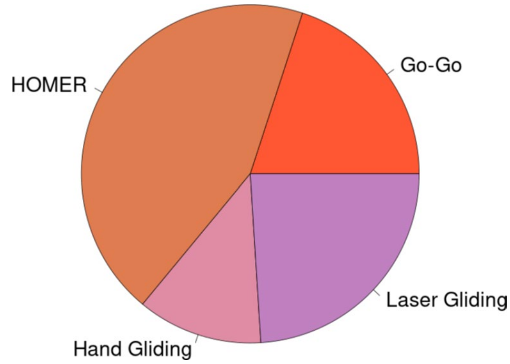

Fig. 15 Reported preferred interaction technique

Table 11 Mean RPE scores (z-scored; scale −1.5 to +1.5). A higher number denotes higher exertion

	RPE
Go-Go	0.19 (0.88)
HOMER	-0.24 (0.95)
Hand Gliding	0.41 (0.88)
Laser Gliding	**−0.36 (0.54)**

Table 12 Mean NASA-TLX results (scale 1-21)

	Mental demand	Physical demand	Effort	Frustration
Go-Go	7.36 (5.20)	9.80 (4.55)	9.24 (4.48)	**3.92 (3.73)**
HOMER	**6.40 (3.58)**	**6.84 (4.29)**	**7.16 (4.41)**	4.00 (3.14)
H. Gliding	8.84 (5.20)	9.84 (5.68)	9.80 (4.74)	5.64 (4.44)
L. Gliding	8.24 (5.36)	7.60 (5.12)	7.52 (4.84)	4.64 (3.11)

8 Discussion

This study compared four VR techniques for hand-based out-of-reach interaction using a within-subject design. The comparison included two established methods–HOMER and Go-Go–and two novel approaches based on a velocity-to-velocity control function: Hand Gliding and Laser Gliding.

The results indicate that each method is suited to different tasks, with raycasting-assisted techniques generally outperforming Go-Go and Hand Gliding. Notably, Laser Gliding was well-accepted by participants, highlighting the potential of velocity-based mapping for out-of-reach VR interaction.

This section provides a discussion of the feasibility of velocity-to-velocity control methods, the compared of interaction techniques, the implications for both Gliding variants, and the effectiveness of raycasting-aided hand positioning.

It also covers additional considerations and future directions and concludes with an overview of the study's limitations.

8.1 Feasibility of the velocity-based interaction

Though amplifying it, position-to-position control mimics natural limb movement. Velocity-to-velocity control employs a mapping that fully decouples virtual hand placement from the user's hand position. Despite this departure from natural behavior, our findings indicate that users can learn to interact using the velocity-based techniques relatively quickly. Although being initially less intuitive, their learning curve was sufficiently rapid to yield a robust user experience in scope of this study.

A fundamental limitation of positional mapping is that a fixed motor space must control an increasingly expansive interaction space at greater interaction distances, leading to diminished precision. In contrast, velocity-based control does not suffer from this limitation. Once mastered, velocity-based mapping maintains consistent control and precision independently of interaction distance.

From a technical perspective, velocity-based methods are particularly well suited for consumer-grade VR systems that track only the head and hands. In contrast, techniques like Go-Go and HOMER rely on accurate measurements of the user-to-hand distance–a requirement that is difficult to meet without external trackers. When the 'growth' functions in the positional methods are anchored to the HMD position, unintended virtual hand movements occur as users turn their heads, severely limiting their usability.

However, velocity-based control is not without technical challenges. Consumer-grade VR systems can suffer from noisy hand tracking, latency, and occasional occlusion, which can destabilize velocity estimates and introduce jitter in the virtual hand. To mitigate this, smoothing over multiple frames or employing filtering (e.g., Kalman filter, exponential smoothing, or 1€ filter) can be employed to maintain continuity in the virtual hand motion.

In practical deployments, a brief calibration task could support personalized adjustment of the velocity-to-velocity control function. Sensitivity parameters may be tuned to match individual motor profiles or preferences, and the system could dynamically adapt during interaction. Further discussion on the implementation of velocity-based techniques is provided in Section 8.3.

In summary, velocity-to-velocity mapping not only circumvents core limitations of positional techniques but also opens a pathway for robust and adaptable interaction methods in future VR systems. We conclude that due to its distinct advantages, the velocity-based interaction has a potential to become a widely implemented VR method for interacting with out-of-reach targets.

8.2 Comparison of techniques

The experiment demonstrated that all evaluated interaction methods were effective in fulfilling task objectives, though each exhibited its own strengths and weaknesses. Performance results from the selection and translation tasks and subjective responses indicate that position-to-position mapping was generally easier to understand and control. Especially HOMER was well-received by participants, both in terms of performance and preference. Go-Go was efficient for the rapid selection of random targets but underperformed in the remaining tasks, especially when some form of hand-based interaction (performing a gesture, pressing buttons) was required. Both techniques with raycasting-aided targeting performed well, and they allowed a more comfortably positioned hand when performing additional interaction.

Below, we provide a detailed analysis of the strengths and weaknesses of the tested methods based on the obtained results.

8.2.1 Go-Go

Consistent with other techniques, our implementation of Go-Go introduced two notable improvements over the original design. First, users could disable the technique while the hand was at the distance, enabling fine manipulation that would otherwise be nearly impossible. Second, clutching allowed users to reposition their physical hands to reduce strain, mitigating the need for sustained arm extension during far manipulation.

However, these enhancements were not widely utilized by participants and had minimal impact on the overall usability of the technique.

Strengths of Go-Go

- **Intuitiveness.** By effectively implementing the metaphor of extending the hand to reach distant objects, the technique is easily understood through trial and error.
- **Speed.** Within the predefined boundary, movement speed aligns with that of the physical hand, optimizing selection performance for randomly positioned objects.

Weaknesses of Go-Go

- **Precision.** At greater distances, small physical movements translate into disproportionately large virtual movements, hindering precise interactions such as button presses or object translations.
- **Fatigue.** The method is inherently tiring, with users reporting the lowest comfort levels when interacting with Go-Go.

8.2.2 HOMER

HOMER emerged as the most effective technique in the comparison. It combines the convenience of raycasting-assisted hand positioning with the intuitiveness of position-to-position control. Notably, participants used the option to deactivate the technique at a distance more frequently with HOMER than with other methods. The higher deactivation rate compared to Laser Gliding highlights the challenges of precision loss at greater distances. It also underscores the value of raycasting-based hand positioning for subsequent interactions without manipulated CD gain.

Strengths of HOMER

- **Speed.** HOMER integrates the rapid hand displacement using raycasting with the efficiency of strongly amplified small movements mapped to distance, particularly in fixed-distance manipulations such as object translation.
- **User acceptance.** The technique performed well across multiple metrics, including NASA-TLX, embodiment, and subjective preference.

Weaknesses of HOMER

- **Precision.** As demonstrated in the keypad task, amplified depth-wise movements at a distance reduce precision.

8.2.3 Hand Gliding

A slightly modified version of Hand Gliding, compared to its pilot implementation, was evaluated in the main study. The results revealed a critical issue: the interaction speed was too low, requiring excessive effort from users. Compared to the pilot study, Hand Gliding performed slower and was not well received by participants, who found interaction particularly demanding at greater distances.
Hand Gliding ultimately lost much of its competitive viability due to the underperformance of its velocity mapping control function. This issue is further discussed in Section 8.3.

Strengths of Hand Gliding

- **Velocity mapping.** The velocity-based mapping prevents amplification of fine movements while still allowing acceleration during the ballistic phase of movement.

Weaknesses of Hand Gliding

- **Speed.** Users had to move their hands excessively fast to reach distant targets or rely heavily on clutching, likely due to insufficient gain in velocity-based control.

8.2.4 Laser Gliding

Laser Gliding performed well across most tasks, demonstrating the feasibility of velocity-to-velocity control. Its success stands in stark contrast to Hand Gliding, which lacked a mechanism easing the initial hand position setting. While velocity-to-velocity control generally requires more practice for precise hand positioning compared to position-to-position techniques, the results indicate that Laser Gliding performed comparably to HOMER. The efficiency of the velocity-based mapping was particularly evident in the keypad task. In distant interactions, the finer control afforded by velocity-based input surpassed even the higher intuitiveness of position-based methods.

Strengths of Laser Gliding

- **Speed-precision balance.** Raycasting-assisted hand displacement, combined with the enhanced precision of velocity-based control at greater distances, made the technique particularly effective for the remote keypad task.
- **Comfort.** Laser Gliding was well received by participants, yielding the lowest perceived exertion and providing good comfort in physical hand positioning during interaction.

Weaknesses of Laser Gliding

- **Intuitiveness.** Compared to HOMER, velocity-to-velocity mapping was less intuitive than position-to-position mapping, as indicated by both subjective and performance metrics.

8.3 Discussion of the gliding techniques

The comparison of results between Hand Gliding and Laser Gliding highlights Hand Gliding's main deficiency: the initial movement toward the target (the ballistic phase of movement in terms of the optimized initial impulse model). This is evident from the keypad HDSS at $4vc$, when compared to the other methods at the same distance (Fig. 12). Further evidence is provided by the suboptimal depth-wise physical hand positioning during keypad interaction (Table 8).

However, the issue was not limited to depth-wise positioning but extended to interaction speed in general. HDSS in the pilot study was $0.69\mathrm{m\,s^{-1}}$ ($SD = 0.47$) in the second run of the selection task, whereas the main study implementation yielded only $0.35\mathrm{m\,s^{-1}}$ ($SD = 0.11$) in the rapid selection task, which was the final task with each interaction method. Different approach to gesture activation of the method (see Section 8.5.3) also contributed to the difference in interaction speeds.

The outlined issue depends on the specific implementation of the technique. A translation function with higher gain could easily mitigate this limitation. In particular, amplifying faster movements into greater movement speeds could alleviate the issue. Additionally, since depth-wise movement in Hand Gliding was particularly challenging, depth-wise translation could be scaled with a greater factor than other movement directions.

In practical deployments of the technique, calibration through a training task could be used to adjust the sensitivity of the translation function. This would enable a personalized velocity-to-velocity control, adapting sensitivity based on user proficiency–similar to how computer mice and touchpad sensitivity settings can be adjusted. The translation function could even dynamically adapt based on user actions (e.g., increasing sensitivity after repeated high-velocity movements are detected).

Another possibility is to combine velocity-to-velocity and position-to-position mappings. The depth-wise position of the virtual hand relative to the user could inform the velocity-to-velocity translation function, scaling up movement speed when the hand is steered to a greater distance. However, these approaches would compromise the advantages of a purely velocity-based interaction.

8.4 The efficiency of raycasting

The results indicate that raycasting for the initial HDS is more effective than methods relying on steering during the ballistic phase. This was particularly evident in the performance differences between Hand Gliding and Laser Gliding, which differ only in their use of raycasting for the initial phase of hand repositioning. Laser Gliding's average HDSS was approximately 33% higher than that of Hand Gliding. In the consecutive remote selection task (number-punching in the keypad task), Laser Gliding outperformed Hand Gliding with statistical significance.

Raycasting-aided methods also yielded the highest comfort levels regarding hand posture and performed exceptionally well in subjective evaluations. Notably, despite the instantaneous nature of hand displacement, these methods did not show reduced embodiment measures, contrary to what might have been expected.

Although we have already discussed steering speed in Gliding methods as a bottleneck, it remains unlikely that optimizations in this area would surpass the convenience of raycasting. The efficiency of raycasting underscores the advantage of instantaneous HDS, demonstrating that steering the hand to a remote destination is generally suboptimal–except in cases such as rapid selection of randomly positioned targets in VR space. This suggests that an optimal hand-based out-of-reach interaction technique should incorporate a fast or instantaneous hand repositioning step (e.g., raycasting, cone-casting, or another method following the same principle), regardless of whether the subsequent interaction phase employs position-to-position or velocity-to-velocity mapping.

8.5 Additional considerations and future work

8.5.1 Why was embodiment so high?

Participants in the current study reported a clear SoO and SoA over the 'flying' virtual hand, comparable to what is experienced with a normally positioned VR hand. The results of the embodiment questionnaire were unexpectedly high, with a mean SoO rating of 5.4 out of 7 points.

Interestingly, both positional- and velocity-based out-of-reach interaction techniques yielded high embodiment scores. This result suggests that sensorimotor contingency, rather than strict anatomical plausibility, plays a critical role in generating embodiment. Although velocity-based mapping departs from natural hand kinematics, its predictable and consistent response appears sufficient for users to integrate the virtual hand into their body schema. This finding supports the idea that in VR environments, human cognitive system can flexibly adopt non-naturalistic mappings, especially when such mappings support interaction or task performance.

A natural extension of this investigation would be to explore SoO in scenarios involving full-body avatars, with virtual arms and hands that can extend on demand while remaining connected to the avatar's body. Although practical challenges for interaction remain (e.g., occlusion of interactable objects), the cognitive psychology of on-demand extended bodies (beyond traditional tool use) is a novel and underexplored area. Future research should also investigate whether these strong results on the SoO can be replicated using objective measures, as the questionnaire results may have been influenced by demand characteristics.

8.5.2 Do the users need control over the whole area?

The main conceptual difference between HOMER and Laser Gliding is that HOMER provides control over the entire space between the user and the target. This approach, perhaps unnecessarily, overloads the motor space by mapping movements to a large control space.

For interaction at a fixed distance (e.g., in the keypad task), unamplified positional mapping may be sufficient. Alternatively, a positional mapping that amplifies hand movements based on the user's distance from the interactable target could be employed–allowing larger, more distant objects to be controlled with higher gain. However, such amplification does not necessarily need to cover the entire user-target distance.

Additionally, users could be provided with a hand-return mechanism when holding a target object in these scenarios. This would naturally mirror the instantaneous step of positioning the hand at a distance using raycasting.

8.5.3 Is the toggle-activation better than holding the gesture?

In the main study, the activation gesture functioned as a toggle, switching interaction techniques on or off, whereas in the pilot study, the gesture had to be sustained throughout the entire duration of hand steering (details in Section 3.3).

The pilot implementation facilitated easier transitions between velocity-based control and unamplified position-to-position control with a positional offset. While the final implementation approach facilitated finer movement control with velocity-to-velocity mapping, it also made it more challenging to traverse larger distances, as it required either greater ballistic movement velocity or repeated movements.

Determining which approach is more suitable likely depends on the usage context. While the sustained gesture led to interaction issues in pilot testing, it provided a balanced use of the positional and velocity-based mapping. Consequently, it may ultimately prove more efficient for velocity-based control mappings in certain scenarios.

8.5.4 Beyond the test tasks

Bimanual manipulation presents another interesting context for out-of-reach interaction. Velocity-to-velocity methods offer unique advantages for bimanual interaction, as they avoid positional mapping complications arising from differences in the 'growth' functions between hands. The origin (shoulder) differs for each hand, and in techniques based on HOMER, so does the gain in the translation function–unless the raycasting step is performed with the exact physical hand position and virtual target position.

8.5.5 Beyond manual control

Eye-tracking is a promising approach to VR interaction. The combination of eye-tracking with hand-based out-of-reach interaction could prove highly effective. Eye-tracking would be particularly useful for the initial HDS step, replacing the raycasting step in HOMER and Laser Gliding. With the currently operated hand free for interaction during gaze-aided HDS, a gesture could be used to initiate hand transfer to the destination defined by gaze, consequently increasing the speed without compromising targeting precision.

8.6 Limitations

8.6.1 Study design

Although the within-subject design is primarily a strength of this study, it also made the experiment relatively long. Prolonged VR interaction can lead to both increased fatigue and improved proficiency over time. Additionally, we chose not to fully randomize the order of techniques to ensure that participants first experienced amplified position-to-position or velocity-to-velocity interaction before learning to control raycasting. However, this approach to managing learning increments may have put non-raycasting methods at a disadvantage.

While some questionnaires likely did not provide much additional value when administered after each condition (e.g., embodiment questionnaire results were quite similar between conditions), certain questions could have yielded more valid responses if presented after each task–particularly for assessing subjective metrics such as frustration. This could be easily implemented with brief in-VR questionnaires.

8.6.2 Clutching implementation and usage

We provided users with clutching and the option to deactivate the technique at a distance, ensuring that all techniques could be used to navigate to out-of-reach objects while also allowing interaction without movement amplification. This design choice aimed to increase ecological validity, as some techniques (especially Go-Go and HOMER) would likely be impractical in modern VR without a properly implemented clutching and deactivation mechanism. However, introducing these control options also added to the complexity of the tasks.

Additionally, the implementation using a fist gesture led to detection issues in the VR system. Specifically, users' fingers were often obscured when performing this gesture, causing tracking failures. As this issue was identified during pre-testing of the experiment, all participants were informed about it and given a simple workaround (rotating their hands while performing the gesture). While this solution resolved the tracking problem for most participants, hand tracking and pose detection systems did not always detect user intentions instantaneously.

Overall, clutching and deactivation functionality increased the difficulty of interaction in the study, and their uneven usage likely contributed to greater variance in the results. While we do not discourage the use of these options in future implementations of interaction techniques, they should be carefully designed with an emphasis on intuitive usability, particularly for ad-hoc tasks in research studies.

8.6.3 User comfort

Although participants were encouraged to prioritize comfort, this was often not reflected in their behavior. Likely due to the additional cognitive demands of control methods that were not essential for task completion, many users chose not to utilize clutching and instead continued the trial even when in uncomfortable positions. In some cases, they reset their hand position and initiated a new HDS in the following trial rather than using clutching during interaction.

While this behavior could likely be mitigated with improved implementation of the clutching gesture, we highlight this pattern of users prioritizing perceived efficiency in task completion over maximizing comfort and natural interaction.

9 Conclusions

This paper presented a within-subject study comparing two position-to-position out-of-reach interaction techniques (Go-Go, HOMER) and two velocity-to-velocity techniques (Hand Gliding, Laser Gliding). The latter two techniques were developed and implemented as part of this research, with Hand Gliding first evaluated in a pilot study.

The study demonstrated the feasibility of velocity-to-velocity methods while identifying limitations in their implementation. Laser Gliding, a velocity-based technique augmented with raycasting for initial hand positioning, performed comparably to HOMER in both efficiency and comfort. The primary advantage of velocity-to-velocity techniques over position-to-position methods lies in their improved precision for distant manipulations and their independence from torso tracking, making them more suitable for consumer-grade VR systems.

As HOMER and Laser Gliding were the most successful techniques across the tested tasks, a key finding is that interaction methods incorporating raycasting for initial hand placement outperformed those relying solely on hand steering. This advantage was consistent regardless of whether the subsequent interaction used position-to-position or velocity-to-velocity mapping. Go-Go and Hand Gliding performed less successfully; in the case of Hand Gliding, the low gain of the translation function likely hindered its usability.

The superiority of raycasting for initial hand positioning suggests that hybrid approaches, combining fast hand relocation with refined manipulation techniques, may offer the most effective solutions for VR interaction. Beyond employing efficient hand displacement strategies, our findings also highlight the importance of integrating an optimized translation function in out-of-reach interaction techniques. While velocity-to-velocity methods offer advantages in precision and hardware compatibility, their usability depends on effective control mappings. Future work should further explore adaptive control strategies and user-specific optimizations to enhance both the efficiency and usability of these interaction techniques.

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Data availability The data that support the findings of this study are available from the corresponding author, F.Š., upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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