

# Redirected Pinch: Efficient and Comfortable Bare-Hand Interaction for 2D Windows in VR

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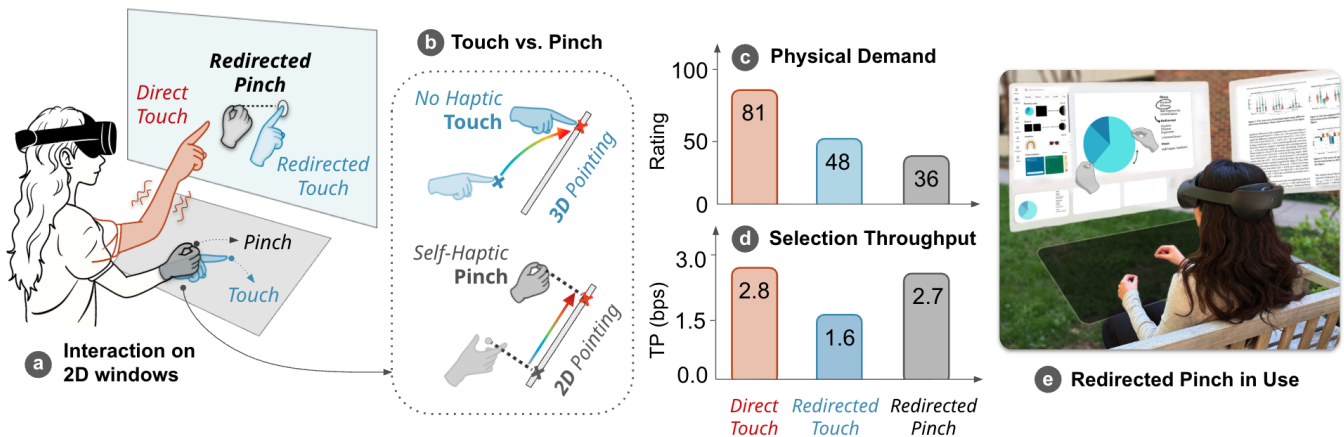
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**Figure 1:** (a) We investigated common techniques for interacting with 2D windows in VR and found: (c) direct touch is efficient but physically demanding; (d) input remapping improves ergonomics but reduces efficiency due to (b) difficult mid-air 3D movement control and unreliable touch confirmation. (e) We introduce Redirected Pinch, a novel bare-hand interaction technique that combines pinch with input remapping to reduce demanding hand-movement control and provide explicit confirmation, allowing users to interact efficiently with 2D windows in VR while maintaining a comfortable posture.

## Abstract

Virtual Reality (VR) offers portable and flexible workspaces. However, enabling efficient and comfortable interactions without external input devices remains challenging. We propose leveraging redirected input to enable comfortable and touch-like interaction for quick and intuitive control. Our design study revealed that while touch interaction performs well with direct input, its performance degrades significantly under input redirection. In contrast, using pinch improves redirected input by providing self-haptic feedback and reducing input dimensionality, thereby compensating

for spatial discrepancies. Based on these findings, we introduce Redirected Pinch, a bare-hand interaction technique that combines input redirection with pinch confirmation. It creates a virtual plane at waist height, remapping hand movements on the plane to a vertical window, with pinch gestures used for confirmation. A user study demonstrated that Redirected Pinch achieves a strong balance of accuracy, efficiency, comfort, and sense of agency across fundamental interactions.

## CCS Concepts

• Human-centered computing → Gestural input; Virtual reality.

## Keywords

gestures, bare-hand interaction, input remapping, virtual reality

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**ACM Reference Format:**

Wen Ying, Yeonsu Kim, Adil Rahman, Erzhen Hu, Geehyuk Lee, and Seongkook Heo. 2026. Redirected Pinch: Efficient and Comfortable Bare-Hand Interaction for 2D Windows in VR. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems (CHI '26), April 13–17, 2026, Barcelona, Spain*. ACM, New York, NY, USA, 18 pages. <https://doi.org/10.1145/3772318.3791512>

**1 Introduction**

Virtual Reality (VR) is emerging as a promising platform for productivity tasks, offering portable, extendable, and distraction-free workspaces that adapt to user needs and contexts [29, 39, 59, 66, 70]. Commercial headsets like Meta Quest 3 and Apple Vision Pro already support desktop-like workflows while enabling large, reconfigurable virtual screens accessible anywhere. Despite the three-dimensional nature of VR environments, many productivity applications continue to rely on two-dimensional (2D) interfaces, such as media editing, document review, and web browsing, as 2D layouts remain familiar, efficient, and cognitively lightweight [12, 13, 24, 28, 36, 75]. However, supporting efficient and comfortable interaction with such 2D windows in VR remains a critical challenge.

Common VR interaction methods, such as using handheld controllers, often lack both precision and comfort during prolonged use [71]. External devices like mice [31], keyboards [30, 40, 42], and tablets [12, 13, 28] can provide more accurate control but at the cost of portability, while also requiring physical surfaces for support. With hand tracking integrated into commercial headsets, bare-hand interaction offers a natural, lightweight, and always-available alternative [43, 45], capable of enabling more dexterous input than device-constrained methods [48, 58]. However, bare-hand interaction lacks tangibility and stability, making it inefficient for precise input [34, 49], and it induces fatigue when arms are kept elevated, known as the “Gorilla Arm” effect [9, 32].

To reduce fatigue and extend reach, researchers have explored input remapping, which manipulates the spatial relationship between real and virtual hands. The Go-Go technique [64] introduced non-linear reach extension, and subsequent work has amplified small arm movements for large-window interaction [52] or redirected near-body hand motions onto far-away windows for more comfortable input [16]. While effective for ergonomics, input remapping can introduce visual-motor mismatch, disrupting proprioception and making mid-air touch less reliable [41, 54]. Complementary work improves input redirection using physical surfaces or custom haptic devices [27, 54], but such approaches reduce mobility and are not always available for everyday VR use.

Self-haptic gestures offer an appealing lightweight alternative [25, 33, 61, 86]. Pinch provides tactile confirmation through thumb-finger contact and supports robust gesture recognition [18, 62, 79], leading to wide adoption in commercial systems [6, 55]. However, the performance benefits of pinch are not consistent across contexts. Pinch can be slower, more error-prone, and physically demanding in direct mid-air selection [14, 21, 57], yet has shown benefits in indirect interactions such as text entry [26, 41]. We hypothesize that pinch becomes more beneficial in redirected mid-air interaction than in direct interaction for two reasons: (1) its immediate tactile feedback without external devices, compensating for the

uncertainty introduced by spatial remapping, and (2) its reduced input dimensionality, as 3D positioning is transformed into 2D motion with a binary pinch confirmation gesture, mitigating accuracy issues caused by depth perception challenges in redirected spaces.

In this paper, we present Redirected Pinch, a novel bare-hand interaction technique that combines pinch with input remapping to enable efficient and comfortable interaction with 2D windows in VR (Figure 1). Redirected Pinch creates a tilted virtual plane at waist height, decoupling the visual workspace from the control space for more ergonomic interaction [4, 16]. Hand movements relative to this plane are remapped in both position and orientation to the application window, while pinches provide self-haptic confirmation. This design reduces fatigue from elevated postures and compensates for spatial inaccuracies caused by remapping. We developed Redirected Pinch through a design study that explored different input mappings (i.e., direct vs. redirected) and confirmation gestures (i.e., touch vs. pinch). Our findings revealed that while touch worked effectively for direct input, its performance degraded significantly under redirected input. In contrast, pinch enhanced redirected input across accuracy, efficiency, and sense of agency, supporting our hypothesis about the value of pinch in remapped interactions.

Finally, we evaluated the performance of Redirected Pinch against commonly used VR interaction techniques, including direct pinch, gaze pinch, and handray pointer, in both simple selection tasks and more complex docking tasks. The results showed that Redirected Pinch provided the best overall balance of comfort, efficiency, and sense of agency in both tasks. In addition, Redirected Pinch was consistently preferred because it required less effort and offered easier control, particularly during prolonged, complex interactions involving continuous and multi-touch input.

**2 Related Work**

Our work builds on prior research in interaction techniques for 2D windows in VR, input remapping for ergonomic interaction, and haptic support for 2D window interaction in VR.

**2.1 Interaction Techniques for 2D VR Windows**

Despite VR’s spatial affordances, 2D interfaces remain popular because they provide familiar layouts, efficient information organization, and cognitively lightweight interaction for detail-oriented work [36, 75]. Both commercial systems [6, 56] and academic research [43] have widely explored how to effectively interact with 2D windows in VR.

One of the most common interaction techniques is mid-air direct touch, where users interact with virtual objects by physically reaching out and touching them with fingers. This approach uses a direct mapping between physical and virtual hand motion, contributing to intuitive and fast interaction with a strong sense of control [82]. However, direct interaction is limited by the user’s arm’s reach and often leads to arm fatigue during prolonged use [49], known as the “Gorilla Arm” effect [9, 32]. In addition, researchers have raised safety and social acceptance concerns about using direct touch in constrained spaces such as public transport [54, 74].

When interacting with distant 2D windows, ray-casting is a more common technique [15, 49, 82], which projects a ray from the user’s

controller or hand (i.e., handray pointer) on an interface window to enable distant interactions with less physical effort. However, ray-based interaction can feel indirect, lacks the proprioceptive cues of direct manipulation, and may result in reduced precision [60], slower interaction speeds [82], and a weaker sense of agency, particularly in fine-grained tasks [49]. Another way to interact with distant 2D windows is gaze-based method [50, 63, 77]. Gaze enables hands-free targeting by leveraging the user’s line of sight. While gaze is efficient for discrete input because it can rapidly jump between targets, it is less effective for continuous control, as maintaining precise gaze positions over time can be fatiguing and difficult to stabilize [35, 37]. This limitation motivates pairing gaze with pinch gestures to confirm selections and enable continuous input through hand movements [5, 62, 76]. While gaze pinch reduces hand movement and mitigates arm fatigue, it still suffers from low spatial precision, risk of unintentional activation, and high cognitive load introduced by mode switching between gaze and hand control [50, 63, 76].

### 2.2 Input Remapping for Ergonomic Interaction

Similar to desktop setups where input devices rest at a lower, ergonomic position while displays sit higher [67], VR and AR systems can also benefit from separating input spaces and output 2D windows. Although collocated interaction supports intuitive interaction, it is not always comfortable for prolonged use, motivating spatial input remapping to allow input at ergonomic positions while keeping interaction visually aligned with virtual content [4, 10, 38, 81]. For example, the Go-Go technique extends the reach of the virtual hand so users can manipulate distant objects without stretching their real arm [64]. RestfulRaycast reduces arm strain by amplifying small elbow and wrist movements during raycasting on 2D windows [52]. ARPads [16] and Virtual Pads [4] create a virtual interaction plane near the user’s body so that the user can move hands on this plane to indirectly control a cursor on the 2D window. Although these input remapping methods can improve ergonomics, they may increase cognitive load and reduce performance [7], especially in complex tasks [78].

### 2.3 Haptic Support for 2D VR Windows

Interacting with 2D windows in VR remains challenging due to the lack of haptic feedback and the difficulty of controlling movements without physical support, which can lead to uncertain touch registration and reduced efficiency [8, 14, 19, 21, 47, 87]. Such issues become even more problematic when input is remapped, as visual–motor mismatches further disrupt proprioception [41, 54]. Prior work has attempted to address them by introducing haptic feedback through physical surfaces. For instance, tables [19, 54] and tablets [13, 28, 69] can act as input surfaces remapped to 2D windows for more accurate and comfortable interactions, while Ownershift provides redirected hand feedback with vibrotactile cues [27]. While effective, these solutions require external resources that are not always available and may be less practical for mobile VR use [59].

A lighter-weight alternative is self-haptics, which uses the user’s own body as a tactile medium [25, 33, 61, 86]. Among common gestures, the pinch naturally provides tactile confirmation through

thumb–finger contact and is widely adopted in commercial VR systems [6, 55] for its robust recognition and explicit confirmation [18, 62, 79]. However, pinch does not always improve performance, with prior studies reporting slower, more error-prone, and physically demanding results in direct selection tasks [14, 21, 57]. In contrast, studies on indirect interaction tasks, such as text entry, suggest that pinch-based self-haptics can outperform mid-air touch [26, 41]. In addition, most prior work focused on simple tasks such as selection, while real-world productivity scenarios frequently involve complex interactions such as multi-touch gestures and continuous manipulation. It remains unclear whether combining input mapping with bare-hand gestures can achieve both comfort and efficiency in more demanding interactions.

## 3 Redirected Pinch

To combine the intuitiveness of direct input with improved ergonomics and performance, we designed Redirected Pinch, a technique that decouples motor and visual spaces by remapping input on a virtual interaction plane, while pinches reduce input dimensionality and confirm input with self-haptic feedback. Here, we describe each component of Redirected Pinch and how the design was informed through a design study.

Prior work, such as ARPads [16] and Virtual Pads [4], introduced a virtual plane to let users interact with vertical windows from a lower, more comfortable position. Following this idea, we placed the interaction plane near the user’s body to reduce strain and better leverage their proprioception (Figure 2c). Interaction with a virtual window through an interaction plane introduces positional and orientational discrepancies between real and virtual spaces, which may affect the user’s task performance and sense of agency [85]. Prior work mitigated this issue by remapping touch input from a physical plane to the virtual window and visualizing hands on the virtual window as if directly manipulating the window [54]. Although we adopted similar input remapping techniques to provide intuitive control, it remains unclear whether this approach would also benefit bare-hand mid-air interaction.

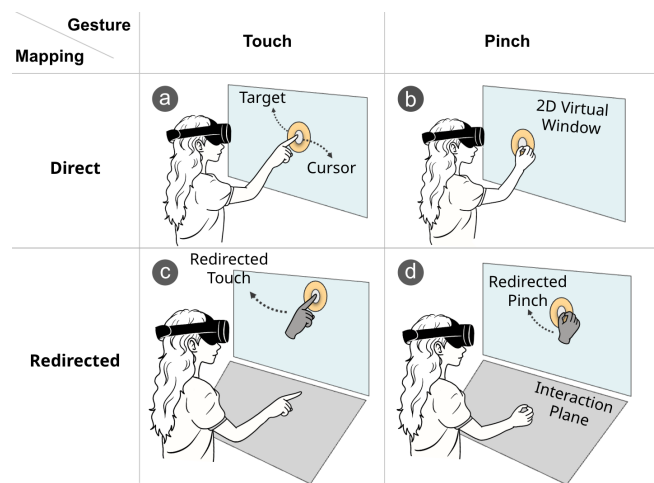
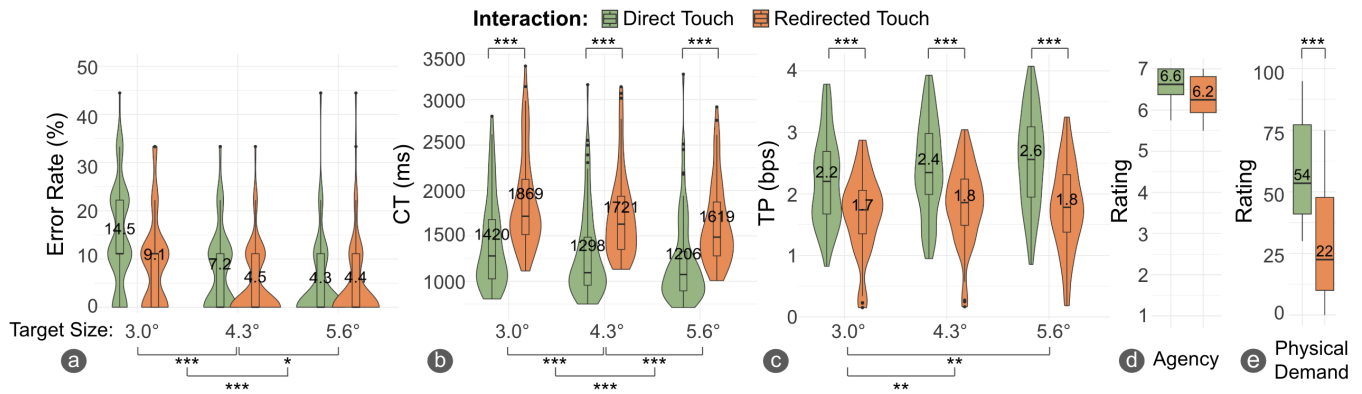


Figure 2: Design options explored in the design study.



**Figure 3: Preliminary study results. (a) Error rate, (b) completion time (CT), (c) throughput (TP), (d) sense of agency, and (e) physical demand using Direct Touch and Redirected Touch. Mean values are shown.**

### 3.1 Preliminary Study: Input Remapping

We conducted a preliminary study to examine how input remapping affects bare-hand interaction, as shown in Appendix A. The study compared Direct Touch, a baseline technique that projects the fingertip onto the vertical 2D window (Figure 2a), with Redirected Touch, a variant that translationally and rotationally remaps hand movements from a lower interaction plane to the window (Figure 2b). However, we found that the typical collision-based touch confirmation method, where a touch is confirmed when the fingertip contacts the window, was difficult to use when input was remapped in 3D. We therefore introduced a speed-based confirmation method, in which a touch is confirmed when fingertip motion slows and reverses, and evaluated both methods for Direct and Redirected Touch.

We conducted a (2 × 2) pilot study with four participants performing the same selection task described in Section 3.2.4. The results showed that the optimal confirmation method depends on the interaction technique. As shown in Appendix A.2, collision-based confirmation resulted in faster and more accurate selections for Direct Touch, while speed-based confirmation reduced errors and improved throughput for Redirected Touch. Participants’ comments aligned with this pattern, noting that collision-based Direct Touch felt intuitive, while speed-based confirmation in Redirected Touch better reflected their intended touch actions. Based on these findings, we used collision-based confirmation for Direct Touch and speed-based confirmation for Redirected Touch in all subsequent studies to ensure each technique operated under its best-performing confirmation method.

After finalizing the design of Direct Touch and Redirected Touch, we recruited 16 participants to complete a 2D Fitts’ law selection task on a vertical window using collision-based Direct Touch and speed-based Redirected Touch. As shown in Figure 3 and Appendix A.4, Redirected Touch showed no significant differences in accuracy or sense of agency and was rated as less physically demanding than Direct Touch. However, it resulted in significantly longer completion times and lower throughput. Participants attributed this performance drop to the misalignment between the interaction plane and their hand movements, which made the cursor “hard to

control.” They also reported “unintentionally tapping” the plane and “difficulty estimating” whether a touch had been registered, noting that Redirected Touch generally required more “energy” and “effort.” These findings motivated the development of Redirected Pinch, designed to retain the ergonomic benefits of redirected input while improving efficiency by using pinch gestures for easier hand-movement control and more explicit confirmation.

### 3.2 Design Study: Input Mapping × Confirmation Methods

While using touch is intuitive and efficient for direct input, it may not be the optimal choice for remapped input. One possible reason could be that mid-air touch lacks haptic feedback, leading to uncertain touch registration and reduced efficiency [21, 47]. Touch also lacks a physical surface to constrain 3D hand movements for efficient control on 2D windows [8, 19, 54, 87]. Using touch requires precise movements along the window’s z-axis, which may increase the control difficulty when input is remapped.

To address these challenges, pinch input has become increasingly popular because it provides a direct sense of tangibility for explicit confirmation [55] and reduces control difficulty by converting 3D interaction into 2D control with a binary confirmation action. Building on these insights, we conducted a design study comparing touch and pinch across both direct and redirected mappings. We adopted the same design of Direct Touch and Redirected Touch tested in the preliminary study.

**3.2.1 Design of Direct Pinch.** We adopted the pinch visualization and detection used in the Meta Quest system [55, 56]. The pinch gesture was visualized with a pinch arrow rendered between the thumb and index finger. The user selected targets as if they were using direct touch, differing only in using a pinch for confirmation instead of a poke (Figure 2b).

**3.2.2 Design of Redirected Pinch.** Redirected Pinch used a tilted interaction plane near the user’s waist (Figure 2d). The user moved and pinched on the plane with real hands, while both hands were translationally and rotationally remapped to the window (Figure

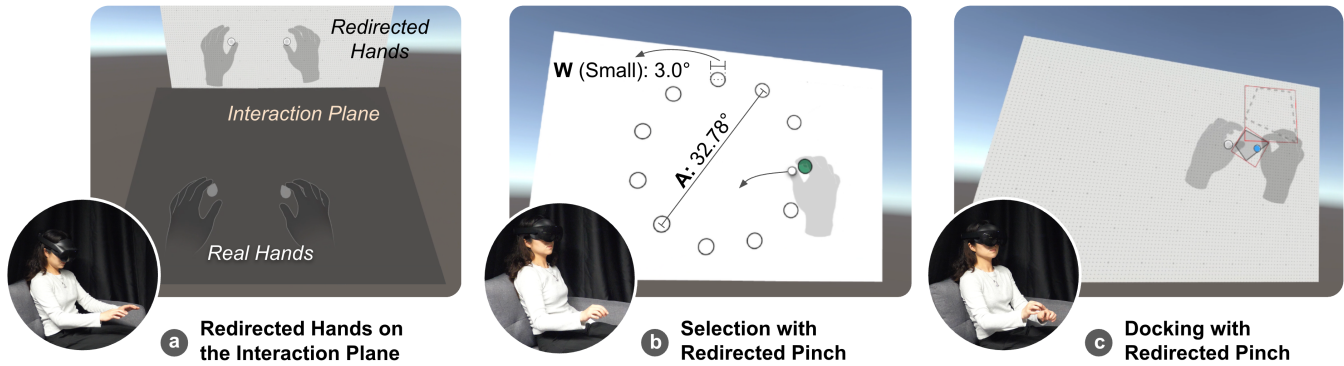


Figure 4: Using Redirected Pinch for Interactions on 2D Windows.

4a). We adapted the cursor control and pinch confirmation of Direct Pinch to the redirected hands. The user’s pinch gesture was visualized with a pinch arrow rendered between the thumb and index finger.

**3.2.3 Window and Interaction Plane Setup.** As shown in Figure 2d and 4a, the virtual window was a vertical rectangle ( $0.75 \times 0.5$  m) placed 0.5 m in front of the participant, within the arm’s reach [19, 22] and filling the headset’s field of view (FOV:  $108.00^\circ \times 95.57^\circ$ ). The interaction plane was the same size to maintain the same Control-Display (C-D) ratio as direct input. The plane was set at a  $45^\circ$  angle relative to the ground, while the virtual window remained upright at  $90^\circ$ , a configuration shown to improve both comfort and task performance [54]. The plane was positioned midway between the user’s body and the virtual window (0.25 m from each), and 0.4 m below the window center, reflecting the average vertical distance from eye to elbow [73]. To minimize distraction, the plane was rendered as a semi-transparent surface that dynamically changes its opacity based on the user’s gaze. When users looked down intentionally, the plane gradually appeared, allowing them to check the plane and real hands as shown in Figure 4a. When they focused on the virtual window, the plane became invisible to avoid distraction as shown in Figure 4b&c.

**3.2.4 Selection Task.** Selection is one of the fundamental tasks in VR [3]. In this study, we implemented a 2D Fitts’ law selection task [16, 22, 77] using WebFitts [2], featuring small circular targets of three sizes: small (diameter:  $3^\circ/26.2$  mm), medium ( $4.3^\circ/37.5$  mm), and large ( $5.6^\circ/48.9$  mm), as shown in Figure 4b. Target sizes were chosen based on prior work [46, 54] and follow established VR target design guidelines [1]. Our pilot study also found that  $3^\circ$  was close to the smallest size that was not occluded by the fingertip (10–14 mm [53]). The distance between the sequential targets was fixed at  $32.78^\circ$  (294.1 mm), chosen to approximate the headset’s FOV while remaining within arm’s reach. Targets appeared in white with a black outline. When a target turned green, participants were instructed to select it as quickly and accurately as possible. Upon a successful selection, the cursor turned blue, and the next target appeared. Unsuccessful selections (cursor outside the target) turned the cursor red to signal the error, after which participants proceeded to the next target.

**3.2.5 Apparatus.** We implemented all interaction techniques using the Meta XR All-in-One SDK in Unity on the Meta Quest Pro. To relieve jitter and smooth hand tracking, we applied a 1€ Filter [17] with parameters  $f_c \text{ min} = 0.9$  and  $\beta = 90$ , following prior work on hand tracking [76, 84].

**3.2.6 Participants.** We recruited 16 participants (5 female, 11 male) from a university. Participants’ ages ranged from 20 to 33 ( $Mean = 25$ ,  $SD = 4$ ), and all were right-handed. Three participants reported using VR weekly, two reported monthly use, and the remaining participants rarely or never used VR. The most common uses of VR were gaming and research studies. The experiment took around 60 minutes, and participants received 20 USD.

**3.2.7 Study Design.** The study was a  $2 \times 2 \times 3$  within-subjects design with three IVs: *Confirmation Gesture (Touch, Pinch)*, *Input Mapping (Direct, Redirected)*, and *Target Size (Small, Medium, Large)*. The order of confirmation gestures and input mappings was counterbalanced. In total, four interaction techniques were tested: *Direct Touch*, *Direct Pinch*, *Redirected Touch*, and *Redirected Pinch*. Each participant completed 660 selections (165 selections  $\times$  2 gestures  $\times$  2 mappings).

**3.2.8 Procedure.** Participants were briefly introduced to the selection study for each of the four interaction techniques. The order of interaction techniques was counterbalanced. At the beginning of each session, participants completed about 2 minutes of training to become familiar with the interaction. Each session consisted of 15 blocks (3 target sizes  $\times$  5 blocks), with a 5-second rest between blocks. After each session, participants completed four questionnaires and took a 3 – 5 minute break before the next session. After testing both techniques, participants completed a survey to rate the four interaction techniques and provided feedback. Participants wore a headset and completed the task while seated.

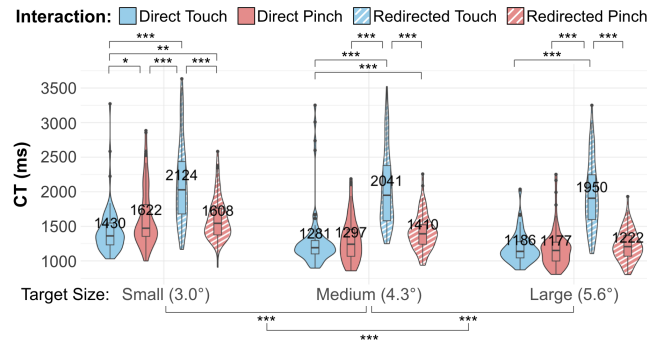
**3.2.9 Selection Evaluation.** Selection performance was evaluated using task completion time (CT), Fitts’ law throughput (TP) [44, 77], and error rate [72]. CT was defined as the time from target appearance until selection, also referred to as Movement Time (MT). A selection error occurred when the participant confirmed a selection, but the cursor was outside the target. TP, which combines speed and accuracy, was calculated using the effective Index of Difficulty and MT, following the ISO 9241-9 standard [51, 68].

**3.2.10 Agency and Workload.** To compare sense of agency and perceived workload across interaction techniques, participants completed two self-assessment questionnaires and provided open-ended feedback after each technique. Since alignment between users' actions and virtual responses influences how natural and intuitive an interaction feels [65, 85], we measured sense of agency using a questionnaire assessing ownership, control, causation, and synchrony on a 7-point Likert scale [65]; the overall agency score was the mean of these factors. Workload was measured using the NASA-TLX [20], which evaluated mental, physical, and temporal demand, performance, effort, and frustration.

**3.2.11 Data Analysis.** For parametric measurements, all data were tested for normality. Normally distributed data were analyzed with repeated-measures ANOVA at a significance level of  $p = .05$ , with pairwise t-tests and Bonferroni correction for post-hoc comparisons. For non-normally distributed data, the Aligned Rank Transform (ART) ANOVA [83] was applied for analyzing main effects, and the ART-C procedure [23] was adopted for post-hoc comparisons. For non-parametric measures (subjective ratings), Friedman's ANOVA was used, with Mann-Whitney tests and Bonferroni correction for post-hoc analysis.

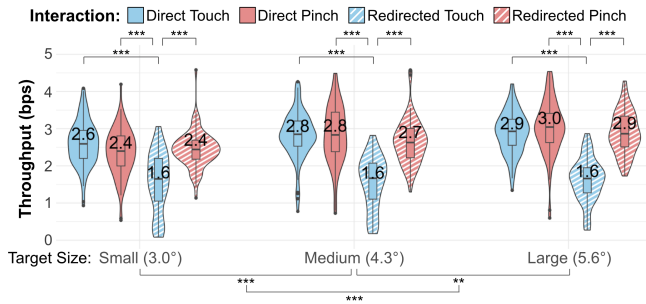
### 3.2.12 Results and Discussion.

**Selection Performance.** Both gesture ( $F_{(1,15)} = 37.2, p < 0.001$ ) and mapping ( $F_{(1,15)} = 75.6, p < 0.001$ ) had significant effects on CT, with a significant interaction between them ( $F_{(1,15)} = 65.2, p < 0.001$ ). As shown in Figure 5, Redirected Touch significantly increased CT compared to other methods ( $p < 0.001$ ). In contrast, no significant difference was found between Direct and Redirected Pinch ( $p > 0.05$ ). Direct Touch needed less time than Direct Pinch ( $p < 0.05$ ) and Redirected Pinch ( $p < 0.01$ ) for small-target selection, and less time than Redirected Pinch for medium-target selection ( $p < 0.001$ ).



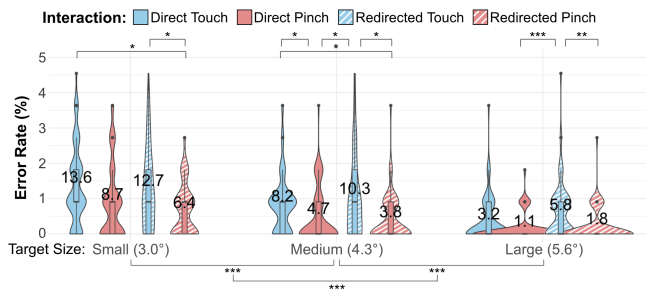
**Figure 5: The completion time (CT) of selecting targets using different gestures (touch, pinch) and input mapping (direct, redirected). Mean values are shown.**

TP was significantly affected by both gesture ( $F_{(1,15)} = 44.0, p < 0.001$ ) and mapping ( $F_{(1,15)} = 100.2, p < 0.001$ ), with a significant interaction ( $F_{(1,15)} = 42.8, p < 0.001$ ) as shown in Figure 6. Post-hoc tests showed that Redirected Touch had significantly lower TP than all other interaction methods ( $p < 0.001$ ).



**Figure 6: Throughput (TP) for target selection across gestures and input mappings. Mean values are shown.**

Figure 7 shows the error rates across interaction techniques. Only gesture had a significant effect on the error rate ( $F_{(1,15)} = 25.7, p < 0.001$ ). For small and medium targets, Redirected Pinch showed significantly lower error rates than Direct Touch ( $p < 0.05$ ) and Redirected Touch ( $p < 0.05$ ). For medium targets, Direct Pinch had lower error rates than Direct Touch ( $p < 0.05$ ) and Redirected Touch ( $p < 0.05$ ). For large targets, both Direct Pinch ( $p < 0.001$ ) and Redirected Pinch ( $p < 0.01$ ) were more accurate than Redirected Touch.



**Figure 7: The error rate of selecting targets using different gestures and input mapping. Mean values are shown.**

**Sense of Agency, Workload, and User Feedback.** As shown in Figure 8, significant differences among interaction techniques were found for controlMovements ( $\chi^2(3) = 13.0, p < 0.01$ ), syncMovements ( $\chi^2(3) = 15.6, p < 0.01$ ), and the mean agency score ( $\chi^2(3) = 14.8, p < 0.01$ ). Participants rated Redirected Touch as having significantly less hand control than Direct Pinch ( $p < 0.05$ ) and less synchrony between real and virtual hands than both Direct Pinch ( $p < 0.05$ ) and Redirected Pinch ( $p < 0.05$ ). Redirected Touch also had a significantly lower overall agency score than other methods ( $p < 0.05$ ).

Figure 9 shows the NASA-TLX workload ratings. Physical demand significantly differed among interaction methods ( $F_{(3,45)} = 7.8, p < 0.001$ ). In particular, Redirected Pinch was rated as less physically demanding than Direct Touch ( $p < 0.001$ ) and Direct Pinch ( $p < 0.05$ ). Redirected Touch received a lower physical demand rating than Direct Touch ( $p < 0.05$ ). Interaction technique also had significant effects on performance ( $F_{(3,45)} = 4.9, p < 0.01$ ), effort ( $F_{(3,45)} = 4.4, p < 0.01$ ), and frustration ( $F_{(3,45)} = 6.8, p < 0.01$ ).

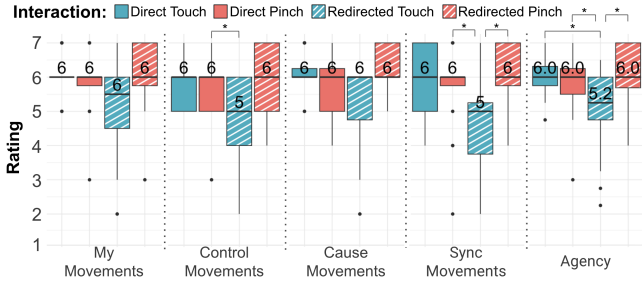


Figure 8: Median ratings for the sense of agency factors across interaction techniques.

0.001). Participants rated Redirected Pinch as having significantly higher performance with lower effort and frustration compared to Direct Touch ( $p < 0.01$ ) and Redirected Touch ( $p < 0.05$ ). Redirected Touch was also rated as more frustrating than Redirected Pinch ( $p < 0.01$ ).

For both direct and redirected mapping, the majority of participants preferred pinch over touch (direct: 10/16; redirected: 14/16) as it was “easy”, “accurate”, and provided more “control” while “less effort” was needed. Overall, 10 of 16 participants selected Redirected Pinch as their favorite technique due to “less fatigue,” “near-body,” and “accurate” control. Four chose Direct Pinch, while two preferred Direct Touch, describing it as “intuitive” with “good synchrony”.

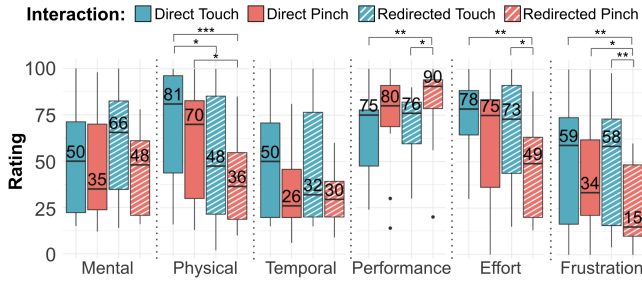


Figure 9: Median NASA TLX ratings for workload factors across interaction techniques.

*Discussion.* While touch gestures were intuitive and fast, Redirected Touch had a significant performance decrease in CT, TP, and sense of agency. Although touch has been widely used in prior work on input remapping, its benefit may stem from the haptic feedback [27] and z-axis constraint provided by a physical surface [54].

In addition, we found that the physical demand for both Direct Touch and Redirected Touch was nearly twice as high as in the preliminary study. One likely reason is that the preliminary study lasted only half as long as the design study. When tasks are extended over time, the reduced physical-effort advantage of Redirected Touch may become less pronounced, while Redirected Pinch continues to retain the ergonomic benefits associated with input redirection.

Focusing on bare-hand interaction without physical objects, we utilized pinch gestures as an alternative to providing self-haptic

feedback and explicit confirmation, reducing the need for hand control along the window’s z-axis. We combined pinch gestures with input remapping and showed the potential of Redirected Pinch to support efficient, comfortable, and easy-to-control interactions.

## 4 Comparative Evaluation

We then evaluated Redirected Pinch more broadly by comparing it with three baseline techniques, including Direct Pinch, Gaze Pinch, and Handray Pointer, across both fundamental selection and complex docking tasks in VR.

### 4.1 Tasks

The selection task (Figure 4b) and window setup were identical to those in the design study. The docking task was designed to investigate the performance of object translation and multi-touch manipulations such as rotation and scaling. We implemented it similarly to docking on a computer using a touchpad [11].

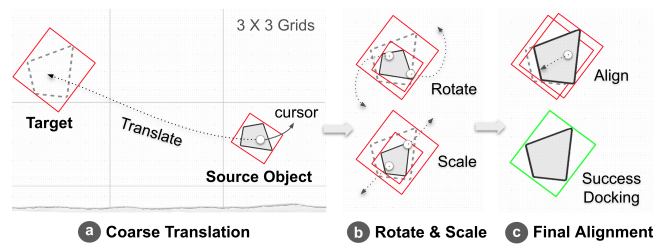
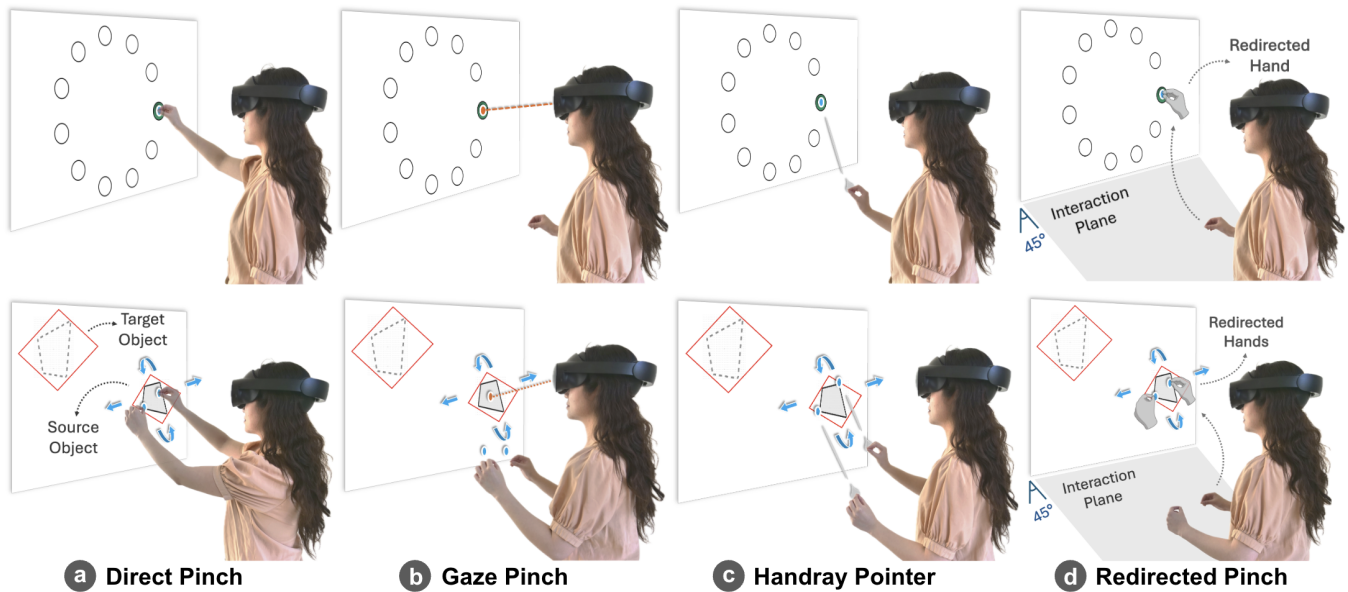


Figure 10: Docking task design. Participants docked the object in three steps: (a) coarse translation toward the target, (b) scaling and rotation to match size and orientation, and (c) optional fine positional adjustment to complete alignment.

As shown in Figure 4c and 10, one irregular source object (150 × 150 pixels) and one target object (250 × 250 pixels) appeared on the virtual window, with the rectangle outlined in red. Participants were asked to dock the source object onto the target by three steps: (1) coarsely translating the source object toward the target position, (2) scaling and rotating the object to match the target’s size and orientation, (3) if needed, performing a final fine adjustment of the object’s position to complete the alignment. Upon successful docking, the outlines of both shapes turned green. The initial position of the target shape was controlled by placing it in the center of one of the equally divided nine cells on the virtual window. The initial distance between the centers of the two shapes was fixed at 500 pixels, and the relative offset angle between them was randomized.

### 4.2 Interaction Techniques

*4.2.1 Direct Pinch.* While Direct Touch and Direct Pinch did not differ significantly in TP or sense of agency (Figure 6 and 8), 10 of 16 participants preferred Direct Pinch. To ensure a fair comparison and minimize confounding effects from differing gesture types, we chose Direct Pinch as the baseline. As shown in Figure 11a, users can pinch with one hand to directly select a target. In the docking task, users pinched the source object to select it and translated it by moving the pinched hand. They then pinched with both hands to



**Figure 11:** We compared (d) Redirected Pinch with (a) Direct Pinch, (b) Gaze Pinch, and (c) Handray Pointer on selection and docking tasks. A blue cursor indicates the user’s hand cursor. Blue arrows show the rotation or scaling manipulation. An orange dashed line indicates the user’s gaze, and an orange circle indicates the gaze cursor.

directly rotate or scale the object, similar to gestures used in Apple Vision Pro [6].

**4.2.2 Gaze Pinch.** Gaze-based interaction is widely explored in AR and VR research [50, 63, 77] and commercial systems like Apple Vision Pro [5]. While typically applied to discrete tasks like selection and challenging to use for continuous control [35, 37], some studies have explored combining gaze with hand input for easier continuous interaction [62, 76]. In this study, we adopted a gaze + pinch technique, similar to that used in Apple Vision Pro [6]. As shown in Figure 11b, users looked at the target while a gaze cursor (orange circle) was rendered at the gazed position, and they confirmed the selection with a pinch gesture. In the docking task, users gazed at the source object and performed a pinch gesture to select it. They then translated the object to the target position by moving the pinched hand. Rotation and scaling were performed by pinching with both hands and moving them accordingly.

**4.2.3 Handray Pointer.** Handray Pointer is one of the most common interaction techniques used in current VR systems. As shown in Figure 11c, users performed selections by controlling the visual ray rendered between the thumb and index finger. The ray was cast toward the virtual window to control the cursor, and selections were confirmed with a pinch. In the docking task, users aimed the ray at the source object and selected it with a one-handed pinch. They translated the object by moving the ray, and rotated or scaled it by pinching with both hands and adjusting the two rendered rays and corresponding cursors.

**4.2.4 Redirected Pinch.** Users used the same Redirected Pinch technique for target selection as in the Design Study. In the docking task, users selected and translated the source object with one redirected

hand. They then pinched with both real hands to rotate and scale the object using the redirected hands (Figure 4c and 11d).

**4.2.5 Hypotheses.** Based on the characteristics of Redirected Pinch and the three baseline interaction techniques, this study aimed to evaluate the following hypotheses:

- *Redirected Pinch* will exhibit efficiency not lower than Direct Pinch and will outperform other common VR input methods in both selection and docking tasks.
- *Redirected Pinch* will enable more comfortable interaction than *Direct Pinch* in both selection and docking tasks.
- *Redirected Pinch* will provide a better sense of agency than *Gaze Pinch* and *Handray Pointer*.

### 4.3 Apparatus

We implemented the four interaction techniques with the same apparatus used in the design study. Eye tracking on the Meta Quest Pro was calibrated for each participant before the session. To relieve jitter and smooth the hand and gaze tracking, we applied a 1€ Filter with parameters  $f_{c\ min} = 0.9$  and  $\beta = 15$  for eye tracking and  $f_{c\ min} = 0.9$  and  $\beta = 90$  for hand tracking [76, 84].

### 4.4 Participants

We recruited 16 participants (5 female, 11 male) from a university. Participants’ ages ranged from 19 to 33 ( $Mean = 27$ ,  $SD = 4$ ). Nine participants wore glasses, and all were right-handed. Most reported limited VR experience: 9 rarely used VR, two used it monthly, and five had never used it. The primary reason for VR use was participation in research studies (6 participants) and gaming, simulation, or general app use (5 participants). The study took around 100 minutes, and the participants received 30 USD.

### 4.5 Study Design

This study consisted of one selection task and one docking task. The selection task was a 4 × 3 within-subjects design with two IVs: *Interaction Technique* (Direct Pinch, Gaze Pinch, Handray Pointer, Redirected Pinch) and *Target Size* (Small, Medium, Large). The docking task was a 4 × 9 within-subjects design with two IVs: *Interaction Technique* (Direct Pinch, Gaze Pinch, Handray Pointer, Redirected Pinch) and *Target Cell* (3 × 3 = 9 grids).

The selection task had 3 blocks for each target size, with each block involving 11 target selections (3 × 3 × 11 = 99). The docking task had 3 blocks for each cell, with each block involving one docking trial (3 × 9 × 1 = 27). In total, the experiment consisted of 504 trials ((99 selection + 27 docking) × 4 interaction techniques).

### 4.6 Procedures

Participants were briefly introduced to the study, which consisted of one selection session and one docking session for each of the four interaction techniques. Eye tracking calibration with the Meta Quest Pro was performed at the beginning for each participant. The order of interaction techniques was counterbalanced using a balanced Latin square design. Tasks were presented in a fixed sequence: selection followed by docking. At the beginning of each session, participants completed a 2-minute training session. Each selection session contains 15 blocks, and each docking session contains 27 blocks, and there was a 5-second rest between blocks. After each session, participants filled out two questionnaires and therefore had a rest of 3 – 5 minutes between each session. After completing all interaction techniques for both tasks, participants filled out a survey to rank the four interaction techniques and provided general feedback.

### 4.7 Evaluation Metrics

We used the same metrics to evaluate selection performance, sense of agency, and workload as introduced in our design study. Since the docking task is distinct, we measured task completion time [11] and counted the number of interactions per trial. Each docking trial consists of multiple interactions, we segmented it into three states as shown in Figure 10: (1) Translate, (2) Rotate & Scale, and (3) Align.

*Task Completion Time.* Task completion time started when the target appeared and ended when the source object successfully matched the target. Based on the three interaction states, we separated completion time into five components: (1) Address, the addressing time from target appearance to the start of translation; (2) Translate, the time spent on translating the object; (3) Rotate & Scale, the time spent on rotating and scaling the object; (4) Align, the time spent on finally aligning the object to the target; and (5) Transition, the interval between the other four phases.

*Interaction Count.* Since participants might perform multiple actions during object translation, rotation and scaling, we also calculated the number of interactions during each docking trial: (1) Translate, the number of attempts for translating the object, (2) Rotate & Scale, the number of attempts for rotating and scaling the object, and (3) Align, the number of attempts for aligning the object.

## 5 Results

### 5.1 Selection Task

*5.1.1 Task Completion Time (CT).* As shown in Figure 12, both interaction technique ( $F_{(3,45)} = 26.4, p < 0.001$ ) and target size ( $F_{(2,30)} = 143.1, p < 0.001$ ) had significant effects on CT. While Redirected Pinch did not differ significantly from Direct Pinch or Gaze Pinch for small targets ( $p > 0.05$ ), it took longer than Gaze Pinch for medium and large targets ( $p < 0.05$ ). Handray Pointer resulted in significantly higher CT than all other techniques across target sizes ( $p < 0.001$ ). On average, Redirected Pinch took 1568.5 ms ( $SD = 403.4$ ) to select a target, while Direct Pinch took 1489.3 ms ( $SD = 427.5$ ), Gaze Pinch took 1430.6 ms ( $SD = 530.5$ ), and Handray Pointer took 2054.8 ms ( $SD = 433.8$ ).

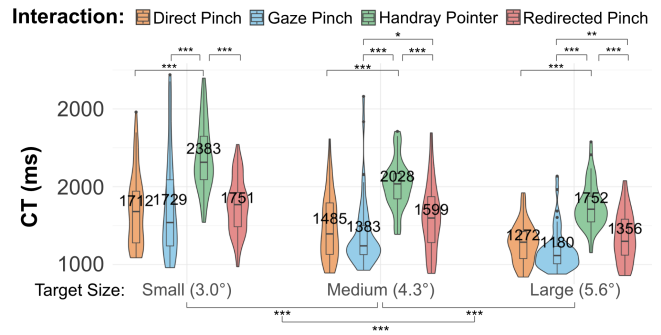


Figure 12: Completion time (CT) for selecting targets using different interaction techniques. Mean values are shown.

*5.1.2 Error Rate.* The selection error rate was significantly affected by interaction technique ( $F_{(3,45)} = 12.9, p < 0.001$ ) and target size ( $F_{(2,30)} = 26.9, p < 0.001$ ). As shown in Figure 13, Redirected Pinch did not differ significantly in error rate compared to Direct Pinch and Gaze Pinch ( $p > 0.05$ ). Both Redirected Pinch and Direct Pinch had a significantly lower error rate than Handray Pointer ( $p < 0.05$ ). Specifically, Redirected Pinch had a mean error rate of 3.17% ( $SD = 5.72$ ), followed by Direct Pinch with a mean error rate of 3.47% ( $SD = 7.05$ ). Gaze Pinch had a mean error rate of 7.39% ( $SD = 11.63$ ), while Handray Pointer led to the worst error rate at 10.61% ( $SD = 10.53$ ).

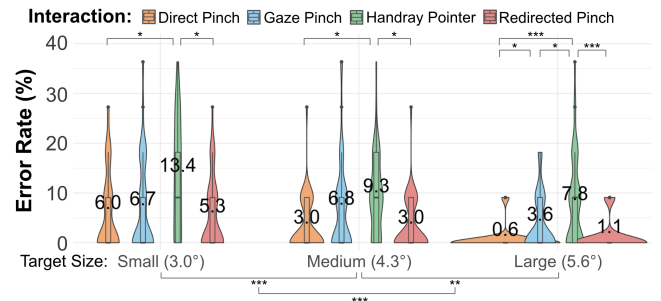
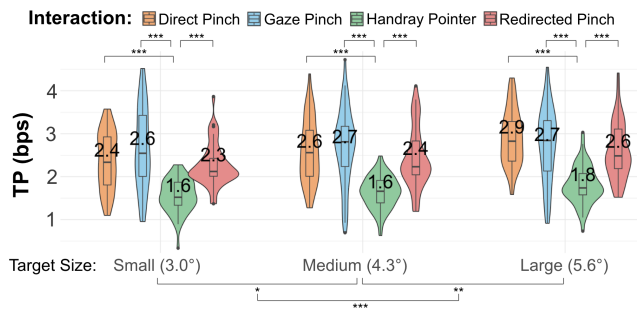


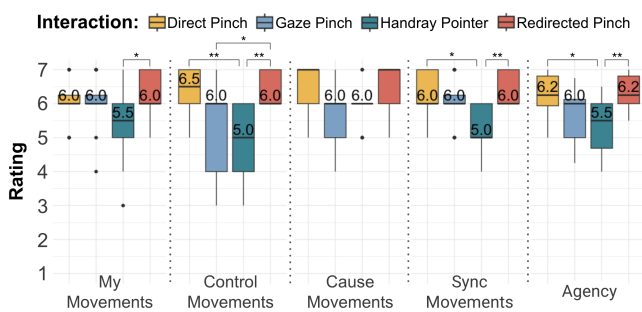
Figure 13: Error rate for selecting targets using different interaction techniques. Mean values are shown.



**Figure 14: Throughput (TP) for selecting targets using different interaction techniques. Mean values are shown.**

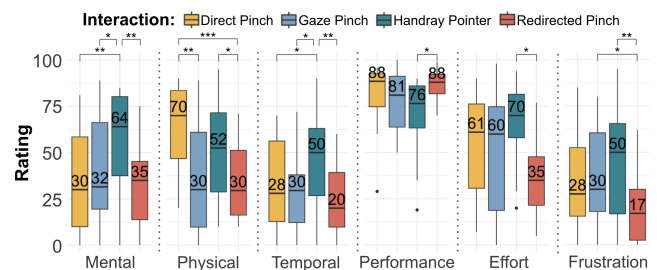
**5.1.3 Throughput (TP).** TP was significantly affected by interaction technique ( $F_{(3,45)} = 23.8, p < 0.001$ ) and target size ( $F_{(2,30)} = 14.5, p < 0.001$ ), as shown in Figure 14. TP of Redirected Pinch was not significantly different from Direct Pinch ( $p > 0.05$ ) and Gaze Pinch ( $p > 0.05$ ). Handray Pointer consistently resulted in lower TP compared to other interaction techniques ( $p < 0.001$ ). On average, Handray Pointer had a mean TP of 1.67 bps ( $SD = 0.41$ ), followed by Redirected Pinch at 2.42 bps ( $SD = 0.63$ ), Direct Pinch at 2.62 bps ( $SD = 0.72$ ), and Gaze Pinch at 2.70 bps ( $SD = 0.89$ ).

**5.1.4 Sense of Agency.** We collected participants' ratings of agency-related questions and plotted them in Figure 15. Interaction technique had significant effects on myMovements ( $\chi^2(3) = 14.1, p < 0.01$ ), controlMovement ( $\chi^2(3) = 20.8, p < 0.001$ ), syncMovement ( $\chi^2(3) = 22.2, p < 0.001$ ), and overall agency ( $\chi^2(3) = 20.9, p < 0.001$ ). With Redirected Pinch, participants reported significantly higher hand movement ownership than Handray Pointer ( $p < 0.05$ ) and stronger hand control than with both Gaze Pinch ( $p < 0.05$ ) and Handray Pointer ( $p < 0.01$ ). Direct Pinch also yielded significantly higher perceived hand control than Handray Pointer ( $p < 0.01$ ). Both Redirected Pinch ( $p < 0.01$ ) and Direct Pinch ( $p < 0.05$ ) resulted in significantly better synchrony between the virtual and real hands compared to Handray Pointer. In summary, Redirected Pinch did not differ significantly from Direct Pinch and Gaze Pinch in the sense of agency. However, Handray Pointer received significantly lower agency scores than Direct Pinch ( $p < 0.05$ ) and Redirected Pinch ( $p < 0.01$ ).



**Figure 15: The sense of agency when selecting targets using different interaction techniques. Median values are shown.**

**5.1.5 NASA-TLX Workload.** Figure 16 presents participants' ratings for each workload factor. Interaction Technique had a significant effect on mental demands ( $F_{(3,45)} = 7.1, p < 0.001$ ), physical demands ( $F_{(3,45)} = 8.4, p < 0.001$ ), temporal demands ( $F_{(3,45)} = 4.9, p < 0.01$ ), performance ( $F_{(3,45)} = 3.7, p < 0.05$ ), effort ( $F_{(3,45)} = 3.5, p < 0.05$ ), and frustration ( $F_{(3,45)} = 5.0, p < 0.01$ ). Post-hoc tests found that Redirected Pinch was rated as less physically demanding compared to Direct Pinch ( $p < 0.001$ ) and Handray Pointer ( $p < 0.05$ ). Gaze Pinch was also rated as less physically demanding than Direct Pinch ( $p < 0.01$ ). Redirected Pinch was perceived to have higher performance than Handray Pointer ( $p < 0.05$ ) and required less effort ( $p < 0.05$ ). In addition, Redirected Pinch was found to be significantly less frustrating than Gaze Pinch ( $p < 0.05$ ) and Handray Pointer ( $p < 0.01$ ). Handray Pointer had significantly higher mental and temporal demand than Direct Pinch ( $p < 0.05$ ), Gaze Pinch ( $p < 0.05$ ), and Redirected Pinch ( $p < 0.01$ ).



**Figure 16: The workload of selecting targets using different interaction techniques. Mean values are shown.**

**5.1.6 User Feedback.** Participants' preferences for interaction techniques varied in the selection task. Redirected Pinch ( $median = 2, IQR = 1$ ) and Gaze Pinch ( $median = 2, IQR = 2$ ) received the highest preference, followed by Direct Pinch ( $median = 2.5, IQR = 2$ ). Handray Pointer was the least preferred ( $median = 4, IQR = 1$ ).

Redirected Pinch stood out for providing a favorable balance of control, accuracy, and comfort (P5: "the best balance of good feeling of control and not being tiring"). 6 out of 16 participants ranked Redirected Pinch as their favorite interaction technique. Participants enjoyed being able to perform accurate tasks while keeping their arms relaxed in a "closer control space" with "less fatigue". Participants also praised that Redirected Pinch felt "intuitive", and P13 added, "Felt like direct pinch without the strain." Despite these advantages, a few participants occasionally forgot to move the actual hands along the interaction plane, but this discrepancy "feels corrected after some use (P11)".

Gaze Pinch was also preferred (7/16) for its low physical effort with minimal hand movements. Many appreciated being able to interact without lifting their arms, as both P4 and P6 mentioned, "I could rest my arm and hand and pinch." However, some participants (4/16) raised concerns about accuracy and eye strain. P2 noted, "Eye tracking isn't that accurate...too sensitive." Additionally, some found prolonged eye use uncomfortable, with P4 stating, "I had to open my eyes for a long time, which induced fatigue."

Direct Pinch was ranked as the favorite one by 3 of 16 participants, who described it as "natural", "straightforward", and "fast",

closely matching their physical movement. However, all participants reported significant physical fatigue due to repeatedly reaching out for target selection.

Handray Pointer was the least favored, with more than half of the participants (10/16) ranking it lowest and describing it as “inaccurate”, “difficult” to control, and increasing “mental stress”. Participants reported issues with ray shakiness and overshooting. P5 commented, “Cursor is always shaky—it takes effort to stabilize it.” Despite these disadvantages, participants appreciated the less hand movement compared to Direct Pinch and the visible ray providing a sense of direction.

## 5.2 Docking Task

**5.2.1 Task Completion Time.** We found that the interaction technique had a significant effect on the CT of docking ( $F_{(3,45)} = 22.2, p < 0.001$ ). As shown in Figure 17, Redirected Pinch and Direct Pinch resulted in significantly less CT than Gaze Pinch ( $p < 0.001$ ) and Handray Pointer ( $p < 0.001$ ), while no significant difference was found between Redirected Pinch and Direct Pinch ( $p > 0.05$ ). Redirected Pinch took 13.17 s ( $SD = 6.07$ ) for one docking, and Direct Pinch took 12.09 s ( $SD = 5.41$ ), followed by Gaze Pinch at 16.16 s ( $SD = 10.32$ ) and Handray Pointer at 17.24 s ( $SD = 6.07$ ). Decomposing CT into different states showed that Redirected Pinch required less time than Gaze Pinch and Handray Pointer, primarily due to shorter translation, multi-touch, and transition times. Direct Pinch also outperformed Gaze Pinch and Handray Pointer across addressing, translation, multi-touch, and alignment times.

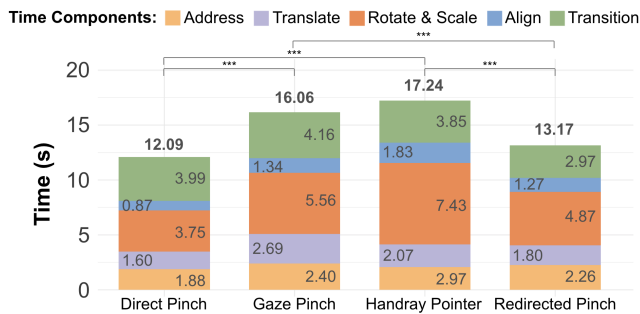


Figure 17: Completion time (CT) and its breakdown for the docking task. Mean values are shown.

**5.2.2 Interaction Count.** Only the interaction technique had a significant effect on the interaction count ( $F_{(3,45)} = 4.1, p < 0.05$ ). Post-hoc tests found that Redirected Pinch (Mean = 6.34,  $SD = 2.12$ ) resulted in significantly lower interaction count compared to Direct Pinch (Mean = 6.98,  $SD = 2.56, p < 0.05$ ) and Gaze Pinch (Mean = 7.26,  $SD = 3.24, p < 0.05$ ) as shown in Figure 18. Redirected Pinch might need the smallest number of interactions, especially during translation, rotation, and scaling. In addition, Gaze Pinch and Direct Pinch were likely to result in more actions during the translation.

**5.2.3 Sense of Agency.** The ratings of sense of agency for the four interaction techniques are shown in Figure 19. Interaction technique had significant differences on the controlMovement ( $\chi^2(3) =$

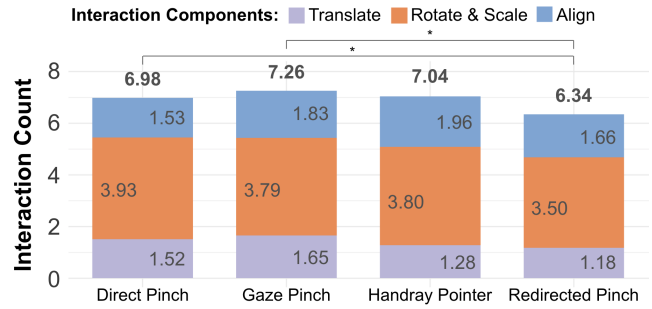


Figure 18: Interaction Count and its breakdown for the docking task. Mean values are shown.

16.9,  $p < 0.001$ ), syncMovement ( $\chi^2(3) = 17.6, p < 0.001$ ), and Agency ( $\chi^2(3) = 19.0, p < 0.001$ ). Both Redirected Pinch and Direct Pinch had significantly higher ratings for the control of hand movements compared to Gaze Pinch ( $p < 0.05$ ) and Handray Pointer ( $p < 0.05$ ). Direct Pinch was also found to have significantly higher sync between virtual and real hand movements than Handray Pointer ( $p < 0.05$ ). In general, Redirected Pinch and Direct Pinch had significantly higher ratings for the sense of agency compared to Gaze Pinch ( $p < 0.05$ ) and Handray Pointer ( $p < 0.05$ ).

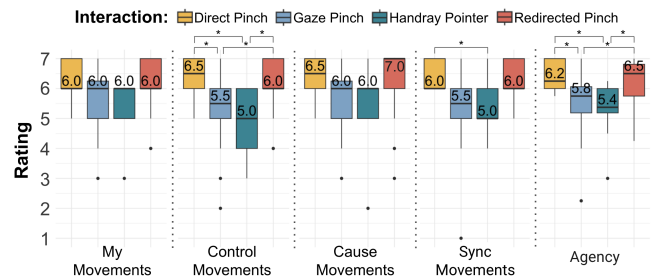


Figure 19: The sense of agency for the docking task using different interaction techniques. Median values are shown.

**5.2.4 NASA-TLX Workload.** Figure 20 shows workload ratings for each interaction technique. Interaction technique had significant effects on mental demand ( $F_{(3,45)} = 9.7, p < 0.001$ ), physical demand ( $F_{(3,45)} = 19.2, p < 0.001$ ), temporal demand ( $F_{(3,45)} =$

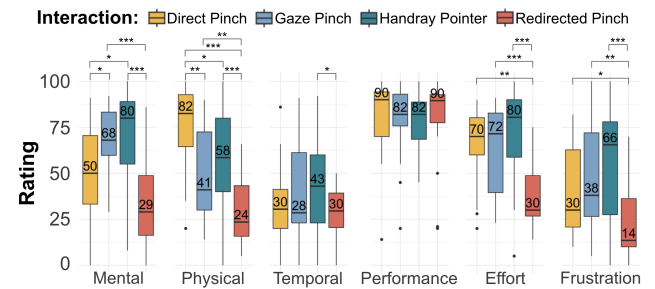


Figure 20: The workload for the docking task using different interaction techniques. Mean values are shown.

3.1,  $p < 0.01$ ), effort ( $F_{(3,45)} = 10.3$ ,  $p < 0.05$ ), and frustration ( $F_{(3,45)} = 8.1$ ,  $p < 0.01$ ).

Redirected Pinch was perceived as requiring the least physical effort, while Direct Pinch was rated as the most physically demanding technique. Specifically, Redirected Pinch was rated significantly less physically demanding than Direct Pinch ( $p < 0.001$ ), Gaze Pinch ( $p < 0.01$ ), and Handray Pointer ( $p < 0.001$ ). Meanwhile, Direct Pinch was found to be more physically demanding than Gaze Pinch ( $p < 0.01$ ) and Handray Pointer ( $p < 0.05$ ). Both Redirected Pinch and Direct Pinch were rated as significantly less mentally demanding compared to Gaze Pinch ( $p < 0.05$ ) and Handray Pointer ( $p < 0.05$ ). Participants reported the lowest mental demand for Redirected Pinch, while Handray Pointer received the highest mental demand ratings. Redirected Pinch was also significantly less temporal-demanding than Handray Pointer ( $p < 0.05$ ). Regarding the effort, Redirected Pinch was rated as significantly lower compared to Direct Pinch ( $p < 0.01$ ), Gaze Pinch ( $p < 0.001$ ), and Handray Pointer ( $p < 0.001$ ). Participants also felt less frustrated when interacting with the Redirected Pinch compared to Direct Pinch ( $p < 0.05$ ), Gaze Pinch ( $p < 0.01$ ), and Handray Pointer ( $p < 0.001$ ).

**5.2.5 User Feedback.** During the docking task, participants strongly favored Redirected Pinch, which received the top median rank for preference (*median* = 1, *IQR* = 0). Direct Pinch followed with a median ranking of 2 (*IQR* = 1), while Gaze Pinch had a median rank of 3 (*IQR* = 2), suggesting more mixed opinions. Handray Pointer was the least preferred method overall, with a median of 4 (*IQR* = 1).

A significant majority (14/16) ranked it as their top choice, highlighting its ease, precision, and reduced fatigue. Participants appreciated that they could perform tasks without raising their arms, still being “quick and precise”. Participants also reported that it felt like a direct method, as P7 stated, “After a while, redirected pinch and direct pinch feel the same, except this [redirected] was less strenuous.”

Direct Pinch was valued for its familiarity and natural “hand alignment”, with 9 participants ranking it as their second choice. For example, P14 noted, “Felt good when you feel like you’re touching it.” While many found the interaction intuitive, 10 participants mentioned it was more “physically demanding” than other methods. The need to reach forward for continuous, precise hand movements made docking even more tiring than selection.

While two participants ranked Gaze Pinch as their favorite choice for reducing “physical strain,” it was generally not favored for its distraction, multi-step input, and “eye fatigue”. Several participants struggled with the coordination between gaze and hand, finding it imprecise and mentally demanding. For example, P2 complained that “Gaze control was annoying because I had to move my hand in two steps to drag the object to [the] target.” In addition, the different navigation speeds between gaze and hand movements were stated as “frustrating”.

Handray Pointer received mixed ratings, with feedback leaning toward negative. Some participants appreciated the reduced arm movement and quick cursor control; for example, P5 stated, “The cursor moved fast with hand movements and not very tiring.” However, it was also the most frequently criticized method, with

more than half of the participants (9/16) ranking it last. 13 participants pointed out issues with control stability and precision, which also caused increased cognitive load, as P2 noted, “I did not like raycasting at all because I had to be too careful and slow.”

## 6 Discussion

Our findings demonstrate that Redirected Pinch effectively balances efficiency, comfort, and sense of agency for interactions on 2D windows in VR. In the selection task, Redirected Pinch was significantly less physically demanding than Direct Pinch due to more relaxed hand movements, and it was less frustrating than Gaze Pinch, which induced eye fatigue and cognitive load. In the more complex docking task, which required both discrete and continuous input, Redirected Pinch was significantly faster than Gaze Pinch and Handray Pointer and required fewer interactions than both Direct and Gaze Pinch. This efficiency benefit may come from the fact that participants did not need to lift their hands or switch between gaze and hand control. Participants also rated Redirected Pinch high in control and agency, and consistently preferred it for being less mentally and physically demanding and causing less frustration.

### 6.1 Enabling Usable Input Remapping

Consistent with previous work, we found that decoupling visual and motor spaces with a virtual interaction plane [4, 16] and redirecting hands with input remapping [54] could reduce fatigue compared to direct input. However, our design studies showed that using touch as a confirmation gesture significantly increased selection time and decreased throughput. This performance degradation was likely caused by three factors. First, the reported misalignment between the visual feedback and participants’ proprioception when using Redirected Touch may have harmed task performance by reducing the sense of agency [16, 54, 81]. Second, mid-air touch without haptic feedback led to uncertainty in touch confirmation [21]. Third, when performing touch gestures, participants’ dominant hand moved not only along the x- and y-axes of the interaction plane to control the cursor, but also along the z-axis (the plane’s normal direction) to confirm touch. Such 3D movement control is known to be challenging, particularly in tasks that require precision [19, 47, 87].

Inspired by the benefits of using a physical surface [8, 54], which constrains the z-axis movements and provides haptic feedback, we decided to leverage pinch for confirmation. Pinch reduces z-axis movement to a simple binary confirmation and provides natural self-haptic feedback [25]. Our study found that Redirected Pinch significantly improved task performance compared to touch-based methods and reduced fatigue compared to direct input. Although our study setup differs slightly from prior work, we also observed that Redirected Pinch achieved higher throughput and lower completion time than remapped mid-air touch [54] and even remapped touch on a physical surface [16], which further validates our design.

### 6.2 Supporting More Complex Interactions

Our study examined both selection and docking tasks, highlighting how interaction techniques benefit across varying levels of task complexity. In selection tasks, all techniques performed reasonably

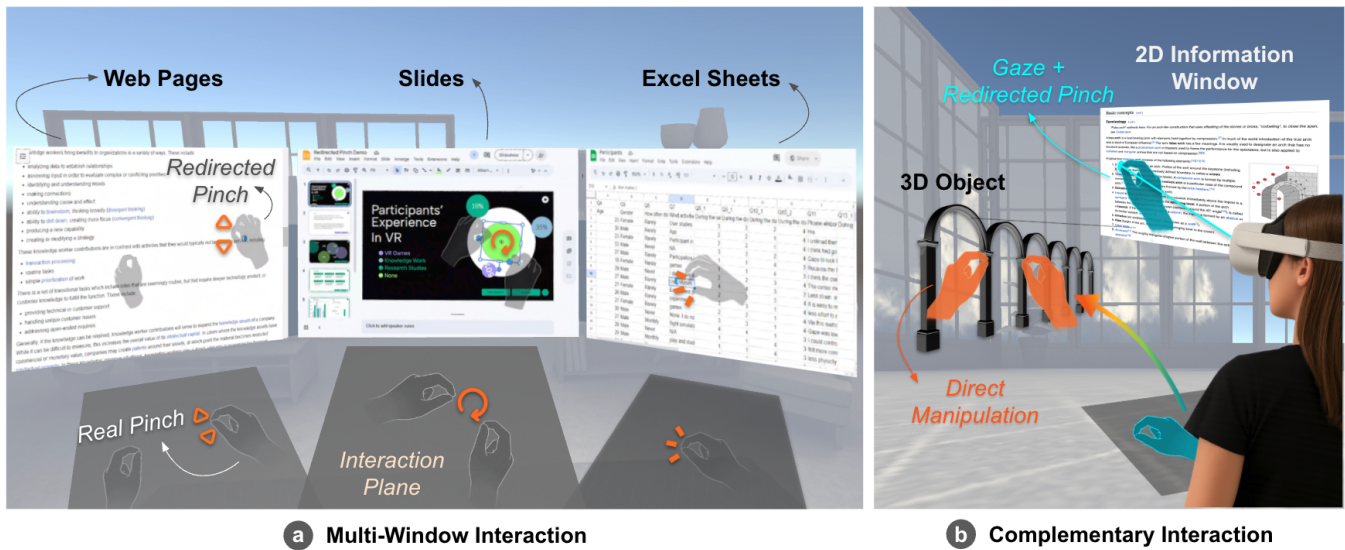


Figure 21: Use scenarios for Redirected pinch: (a) multi-window interaction and (b) complementary interaction.

well except for Handray Pointer, with Redirected Pinch showing no significant difference in selection performance or sense of agency compared to Direct Pinch and Gaze Pinch. Gaze Pinch stood out for its selection speed due to its hands-free control, though it introduced some frustration because of the hand-eye coordination challenge.

The docking task revealed clearer distinctions. Redirected Pinch showed no significant difference from Direct Pinch in task completion time or sense of agency, but it required fewer interactions and led to lower physical effort and frustration. Handray Pointer again underperformed, particularly in fine or multi-touch control, where unstable cursor behavior may have reduced usability. Gaze Pinch for docking had a significant decline in performance compared to the selection task, likely due to difficulty in precise cursor control and frequent mode switching.

Participants' preferences varied across tasks. In the selection task, both Redirected Pinch and Gaze Pinch were favored due to lower physical demand compared to Direct Pinch. In the docking task, participants overwhelmingly preferred Redirected Pinch for its combination of comfort, control, and perceived sense of agency. These findings suggest that complex and multi-step tasks such as docking can better leverage the advantages of pinch with input remapping than simple tasks such as selection. For simple selection, Gaze Pinch and Handray Pointer may be sufficient as they also led to lower fatigue than Direct Pinch, similar to Redirected Pinch. However, their efficiency dropped significantly in the more complex docking task. In contrast, Redirected Pinch maintains the intuitiveness of direct manipulation while supporting more ergonomic and efficient interactions than direct input. As participants mentioned, Redirected Pinch allows them to rely more on proprioceptive cues, reducing the need to consciously track both visual content and cursors. This visual shift from input control to task content may be particularly beneficial for prolonged interaction on 2D windows, as the docking task took more time than selection.

### 6.3 Enabling Adaptive Interaction Plane

While our study employed a near virtual window and fixed the interaction plane size to match the window for experimental control, Redirected Pinch can dynamically adjust C-D gain to suit different input tasks and accommodate different cursor demands on farther or larger surfaces. For example, the interaction plane can be made smaller to increase C-D gain, amplifying the real-hand movements, minimizing physical effort, increasing the reach [81], and supporting faster traversal, especially on larger displays [80]. Meanwhile, on smaller windows, the interaction plane can be aligned more closely with the window size and use a lower C-D gain to support more precise cursor control [80].

In addition, the interaction plane positioning was fixed in our controlled design and comparative studies. However, this setup may not suit users with different body types or arm lengths. Some participants mentioned that the position of the interaction plane was not optimal for them. Allowing users to manually adjust the location and orientation of the interaction plane may lead to a more personalized and ergonomic experience. This adaptation can be further extended to enable automatic, dynamic adjustment of the interaction plane based on a user's recent pinches, similar to what we explored in the preliminary study of Redirected Touch (Appendix A.4.3). As shown in Figure 22, during the selection task, participants gradually shifted their hands from the initial interaction-plane setup, and the plane adapted to these movements, shifting to a lower and more horizontal position and orientation. This tendency toward more relaxed hand positions and comfortable postures may also enhance the naturalness and efficiency of Redirected Pinch, particularly in more complex, realistic tasks that involve prolonged use.

### 6.4 Use Scenarios for Redirected Pinch

Redirected Pinch offers ergonomic and efficiency benefits that can extend beyond our controlled experimental tasks and support richer

productivity workflows in VR. To illustrate its potential, we developed an application demo showing how Redirected Pinch can be used to interact with multiple 2D windows during VR knowledge work. As shown in Figure 21a, a user works with three productivity applications simultaneously: a web browser, a slide editor, and a spreadsheet. In this application, a user can simply look at a window and place the interaction plane in any comfortable position and orientation. The system will then automatically assign the plane to the gazed window, allowing the user to interact comfortably and efficiently using Redirected Pinch.

In addition, Redirected Pinch can also work alongside existing VR interaction techniques. Users can activate it when needed and combine it with other techniques such as gaze-based selection (Figure 21b). If the user's hands move away from the plane toward other objects, the redirected input can be automatically disabled, allowing the user to perform direct touch or grab-based 3D manipulation. This compatibility allows Redirected Pinch to integrate smoothly into broader VR workflows without interrupting other input modalities.

These scenarios demonstrate how Redirected Pinch can generalize to more realistic productivity scenarios and provide a promising foundation for enabling comfortable, efficient, and flexible VR workspace interaction.

## 6.5 Limitations and Future Work

While our findings show the promise of Redirected Pinch for enhancing 2D interaction in VR, several limitations remain. Because the technique relies on hand tracking, tracking performance may influence user performance. This challenge is common to most bare-hand interactions, but the lower hand positions encouraged by Redirected Pinch can be harder for the system to track accurately. Improvements in hand tracking may further improve its effectiveness.

Redirected Pinch also requires a brief familiarization period. Although our study did not reveal significant learning effects across techniques, some participants reported an initial adjustment phase. Longer-term studies may reveal more nuanced learning patterns and provide insight into how users adopt the technique over time.

Additionally, our study fixed the redirection parameters, such as the C-D gain and the position of the interaction plane, to maintain experimental control. A further study investigating how these parameters affect performance and the sense of agency will be important for determining optimal configurations.

Finally, our evaluation used simplified tasks in a controlled lab setting to isolate core performance characteristics. While this allowed for a more controlled evaluation, it does not capture the complexity of real VR workflows. Evaluations in more realistic, multi-window environments with richer task demands would provide a better understanding of how Redirected Pinch performs in actual use scenarios. In addition, exploring more complex interactions, such as extending it to support 3D manipulation, would provide insight into how the technique can generalize beyond 2D windows.

## 7 Conclusion

In this work, we investigated mid-air bare-hand interaction techniques for discrete, continuous, and multi-touch inputs on 2D windows in VR. Through design studies comparing input mapping and confirmation gestures, we propose Redirected Pinch, a novel interaction technique that allows users to perform pinch gestures with comfortable postures while enabling efficient interactions by hand redirection and input remapping. We compared Redirected Pinch with three commonly used methods: Direct Pinch, Gaze Pinch, and Handray Pointer. The comparative evaluation showed that Redirected Pinch provides a strong balance of speed, accuracy, agency, and comfort across both selection and docking tasks. While we tested Redirected Pinch in a controlled study, it can be flexible and adapted to more realistic applications. Future work could explore similar techniques in real-world productivity tasks involving windows of varying sizes, distances, orientations, and multi-window setups.

## Acknowledgments

This work was supported by the IITP (Institute of Information & Communications Technology Planning & Evaluation)-ITRC (Information Technology Research Center) grant funded by the Korea government (Ministry of Science and ICT) (IITP-2026-RS-2024-00436398).

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## A Preliminary Study: Input Remapping

We examined how input remapping influences bare-hand interaction by comparing Direct Touch and Redirected Touch in terms of selection accuracy, throughput, sense of agency, and workload. This study and its pilot studies used the same apparatus, task, and evaluation framework as the design study (Section 3.2), though the interaction plane was described with slight variations to reflect our previous exploratory process. Below, we detail the participants, procedures, and results.

### A.1 Window and Interaction Plane Setup

The virtual window was a vertical rectangle ( $0.75 \times 0.5$  m) placed 0.5 m in front of the participant as shown in Figure 22. Its initial position and orientation were chosen by each participant, typically near the waist at a tilted angle. When performing Redirected Touch, the interaction plane dynamically adjusted to better align with the participant's input. This adjustment was made by smoothly translating and rotating the interaction plane so that it eventually matched the surface fitted based on the most recent 10 touches the participant confirmed.

### A.2 Pilot Study: Touch Confirmation

For Direct Touch, collision-based confirmation resulted in faster and more accurate selections (1106.5 ms CT, 8.33% error rate, 2.81 TP) than speed-based confirmation (1310.3 ms CT, 9.43% error rate, 2.27 TP). For Redirected Touch, however, the speed-based method (1454.3 ms CT, 5.03% error rate, and 2.07 bps TP) substantially

reduced errors and improved throughput compared to the collision-based one (1578.7 ms CT, 20.46% error rate, and 1.69 bps TP). Participant preferences followed a similar pattern. Collision-based Direct Touch was favored because it felt “intuitive and similar to physical touch[es]”. For Redirected Touch, they preferred the speed-based confirmation because it “reflected [their] touch intention” while the collision-based one was “hard to use” because it could cause them to “unwillingly penetrate the surface while moving the hand toward a target” or “hover over the surface when [they] meant to touch”.

### A.3 Participants

We recruited 16 participants (5 female, 11 male) from a university. Participants' ages ranged from 20 to 35 ( $Mean = 26$ ,  $SD = 4$ ), and all were right-handed. Among the participants, two reported using VR weekly, primarily for gaming and app development, while five used VR monthly, often for research and studies. The remaining participants rarely or never used VR. The experiment lasted around 30 minutes, and each participant received 15 USD.

### A.4 Results and Discussion

**A.4.1 Selection Performance.** As shown in Figure 3a, no significant difference was found between Direct Touch and Redirected Touch ( $F_{(1,15)} = 3.97$ ,  $p > 0.05$ ) in selection accuracy. However, the two techniques significantly differed in CT ( $F_{(1,15)} = 29.1$ ,  $p < 0.001$ ) and TP ( $F_{(1,15)} = 19.1$ ,  $p < 0.001$ ). As shown in Figure 3b&c, Redirected Touch resulted in an increased mean CT by approximately 500 ms ( $p < 0.001$ ) and a decreased mean TP by more than 0.5 bps ( $p < 0.001$ ) compared to Direct Touch. These results indicate that Redirected Touch did not meet our goal of achieving interaction efficiency comparable to Direct Touch.

**A.4.2 Agency and Workload.** Despite the performance decrease, no significant differences were found between Redirected Touch and Direct Touch in terms of sense of agency ( $V = 54$ ,  $p > 0.05$ ) as shown in Figure 23a). However, Redirected Touch was rated as significantly less physically demanding than Direct Touch ( $t(15) = 5.78$ ,  $p < 0.001$ ) as shown in Figure 23b. Participants noted that their arms felt less tired with Redirected Touch, but also reported that achieving successful contact with the window was more challenging and less intuitive than Direct Touch.

**A.4.3 Motion Trend of Interaction Plane.** Since the interaction plane was dynamically adapted to users' touches, its changing position and orientation effectively reflected users' hand motion and the interaction surface they implicitly positioned and oriented toward. The plane's movement pattern across blocks is illustrated in Figure 22b&c. Specifically, the plane's height remained relatively stable throughout the task, averaging roughly 0.4 m below the window center, which is close to the typical vertical distance from eye to elbow [73]. In contrast, the plane's orientation gradually shifted from a more horizontal posture toward a more vertical one, converging around a 45° tilt relative to the window. These trends may reflect a natural tendency toward more relaxed hand positions and comfortable postures, a shift from visual alignment toward greater reliance on proprioceptive cues, or a more usable interaction area. Based on these observations, in the later formal design

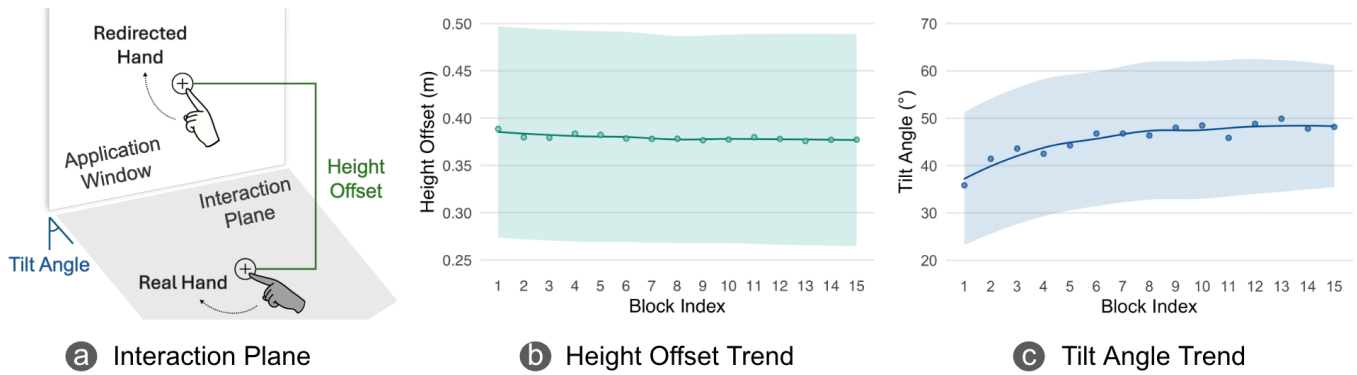


Figure 22: In the preliminary study, participants set up (a) an interaction plane around their waist, which dynamically adjusted its (b) height and (c) angle based on their touch during each selection block.

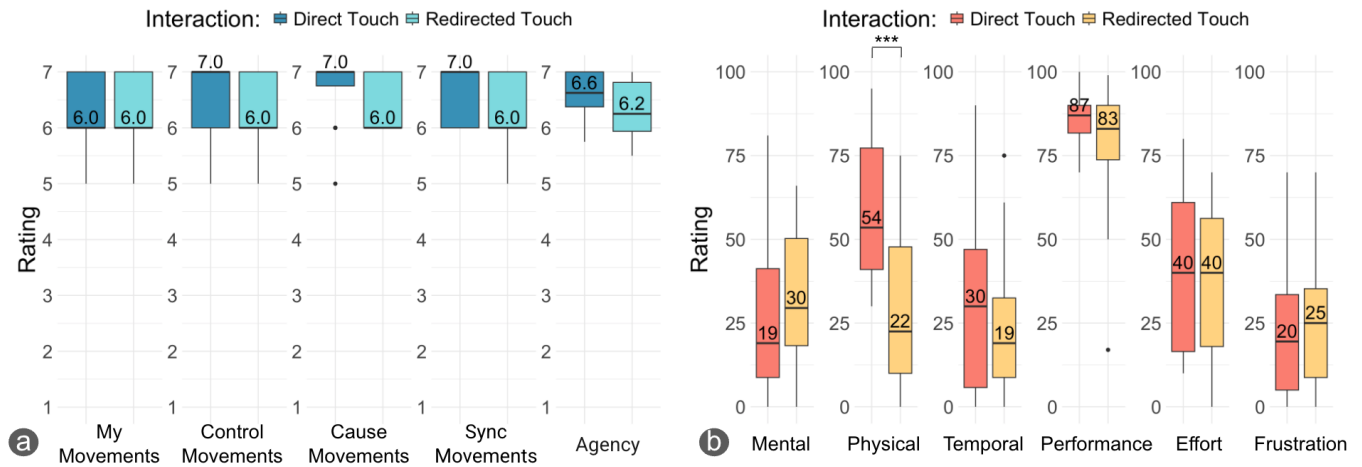


Figure 23: Preliminary study results. (a) sense of agency, and (b) workload ratings using Direct Touch and Redirected Touch. Mean values are shown.

and comparative studies, we fixed the interaction plane at a 45° tilt

and positioned it 0.4 m below the window center to ensure a more comfortable and controlled experimental setup.