Comfort Is in the Air: Investigating the Perceived Comfort of Rotational and Translational Mid-Air Interactions

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Abstract

The degrees of freedom of our arms allow us to easily translate and rotate our hands in front of our bodies. As such, most of the common mid-air input in Extended Reality (XR) builds on these two 3D transforms. However, current research primarily focuses on specific forms and expressions of mid-air input, thereby not providing insights into the comfort and performance of the two gestural primitive building blocks: rotation and translation. To design ergonomic mid-air XR gesture input, we need a thorough understanding of the comfort and performance intrinsic to these two ground-laying building blocks. In this work, we investigate the effects of multiple influences of gestural input, such as interaction placement and complexity, on perceived comfort and performance. Our results reveal comfort preferences for translational interaction, while also highlighting opportunities for rotational-based input. We discuss how these findings can guide designers in creating more comfortable XR experiences and situate our findings within previous work.

CCS Concepts

• **Human-centered computing** → *Gestural input.*

Keywords

Extended Reality, Mid-Air Gesture, Comfort

1 Introduction

The Augmented Humans community envisions systems that extend what people can perceive and do. XR is a promising interface for such augmentation, as it enables ubiquitous access to a digitally augmented world throughout the day. The primary interaction modality for these systems are mid-air gestures. However, prolonged use induces strain and fatigue, limiting the feasibility of sustainable augmentation.

Mid-air interaction in XR commonly relies on translation and rotation [13, 36]. While these transforms themselves are not novel to research, they remain the primitive building blocks of nearly all mid-air gestures: whether users push, pull, drag, dial, twist, or align objects, these actions fundamentally decompose into translational and rotational motions. Despite their central role, prior work primarily investigates concrete gesture designs, use cases, or interaction techniques, leaving the ergonomic foundations of these primitives largely underexplored.

To achieve sustainable augmentation, we must understand the comfort implications of the underlying motions that constitute more complex gestures to make them more ergonomic. In this work, we shift attention from inventing new gestures to understanding how the foundational transforms themselves, translation and rotation(3D MANIPULATION [13, 36]), affect perceived comfort. We additionally study how interaction PROXIMITY, DIRECTNESS, GRANULARITY, and target attributes (TARGET, DIRECTION [25, 26]) shape comfort and performance.

Through a controlled study with 20 participants, we show that translational input is consistently more comfortable and efficient, while rotational input becomes comparably comfortable in specific spatial or fine-granular contexts. Indirect interaction further reduces physical demand without compromising performance. Our findings provide a foundational understanding of comfort across these gestural primitive building blocks, offering actionable guidance for designing more ergonomic mid-air interactions and, ultimately, more sustainable augmented human experiences.

2 Related Work

2.1 Interaction Techniques for Extended Reality (XR)

Previous research examined several XR interaction modalities. They range from specially designed controllers [48, 65] over everyday objects [27, 70] to using the own body as input [14].

When using hardware or objects for input, researchers created numerous customized tangibles and controllers [57, 58]. However, these devices mainly focus on novel interaction techniques, while

comfort and ergonomics are typically not addressed directly. Yet, they benefit from close-to-body interaction and lowered or angled [23] hand posture. Research also explored the possibility of using more everyday objects as input devices compared to specialized hardware. For instance, Al-Sada et al. [1] presented embedded inputs from intelligent wearables to interact with augmented worlds. Additionally, multiple researchers explored even more commonly and daily-used hardware such as smartphones [9, 55], tablets [19, 28], or smartwatches [24, 67]. Using these objects and hardware as input devices still requires them to be carried around, even when not used. This can be cumbersome in on-the-go scenarios.

To this end, research also examined hands-free approaches, requiring no additional hardware carried in the hands, for XR interaction by using gestures. This includes either the whole body [14] or just parts of it such as forearms [17], palms [41], the abdomen [60] or the face [53, 68]. One advantage of using the body as an input device is the presence of passive haptic feedback for the user. Research has shown that even simple passive haptic feedback can increase the accuracy and task completion time [45, 62]. However, these gestures sometimes struggle with social acceptability, as the user prefers less noticeable gestures [2]. For that reason, a multitude of research focused on eye gaze as input [29, 44, 50]. This allows almost unnoticeable interaction with XR applications. Besides gaze, mid-air hand gestures were extensively explored by researchers and became state-of-the-art interaction techniques for modern XR Head-Mounted Displays (HMDs) [8, 33, 61]. Utilizing a combination of hand movement, posture, and gaze allows for convenient and flexible interaction within arm's reach [39, 43]. A great advantage of mid-air gestures is the versatility and flexibility compared to the previously mentioned hardware. For instance, Jahani et al. [21] analyzed over 900 hand gestures just for in-vehicle interfaces, which shows their high versatility. They can adapt to every surrounding, environment, and use case. Thus, mid-air gestures are the default interaction modality in most modern XR HMDs.

Again, most of these approaches investigate interaction concepts and often suffer from physical strain and fatigue when used for a prolonged time, resulting in discomfort and non-ergonomic interactions. Therefore, gaining comprehensive insights into the ergonomics of XR mid-air gestures could benefit from making them more comfortable while still benefiting from their high versatility.

2.2 Discomfort of Mid-air Gestures

While mid-air gestures are versatile and convenient, they are affected by several disadvantages. For example, mid-air gestures result in arm fatigue if the interfaces do not adequately fit the user's ergonomics. When users have to hold their arms in front of the body for a prolonged time without support, they start to feel discomfort induced by the so-called "gorilla arm" [18, 22, 59] effect.

Keeping arms lowered and close to the body was found to be the most ergonomic and comfortable position by multiple prior work [18, 26, 35, 36, 46]. Moving interaction elements to this zone is a naive yet practical approach to allow users to interact in this lowered position. Another solution the researcher proposed was systems and input methods that enabled users to interact with the XR Environment on eye height while allowing them to keep their arms in a lowered position [20, 32, 40, 69]. ErgO [40], for instance, remaps the arm's lower reachable space to a more significant interaction space inside the XR Application. This allows the users to interact with elements at eye height while maintaining their arms in a lowered, comfortable position. A common technique is also utilizing ray-casting to interact with objects at eye height from a distance. A recent work enabled the combination of upper limb movement with raycasting to create "Joint-Amplified Raycasting" [35]. This technique allows a lowered and more comfortable arm position during raycast input in XR.

To allocate these comfortable positions, previous work proposed models [36] and systems [13, 34] to assist designers in finding comfortable interaction zones around the user. RULA [36], for instance, classified postures of the arms, hands, and head in different groups. Based on that, RULA derives a score that ranks the posture on a scale from 1, acceptable posture, to 7, really uncomfortable posture. However, RULA does not account for the interaction duration. Therefore, Hincapié-Ramos et al. proposed the Consumed Endurance [18] rating, including the time spent holding a posture. Similar to RULA, the Consumed Endurance rates the posture of the user. But this time, the system also considers the time spent in the posture. The Consumed Endurance rates worsen the longer a user stays in a pose. In contrast to RULA, the Consumed Endurance is calculated on the fly and not before interacting. Therefore, the XR application can dynamically adapt to the calculated fatigue.

While the Consumed Endurance now considers the time in its calculation, one crucial part of the general interaction is still missing: the action or gesture the user has to perform. Previous work shows that rotational arm movements require more muscle activation and, therefore, induce more strain to the arm than positioning movements [56]. Therefore, rotational and translational interaction should be rated differently regarding perceived comfort. To fully understand the ergonomics and comfortable design of XR Environments, we need a deep understanding of the influence of 3D manipulation gestures, like translation and rotation, on the user's comfort to fully understand the user's convenience.

2.3 Summary

While research shows plenty of ways and opportunities to interact in XR, mid-air gestures are still considered a state-of-the-art interaction modality within numerous HMD application areas. However, previous work also revealed that these interactions can induce fatigue and discomfort, for example, when used for a prolonged time [18, 22] or necessitates a non-ergonomic posture [13]. Contemporary metrics to quantify comfort for mid-air interactions, like RULA [36] and the Consumed Endurance [18] are already helpful tools to assess the user's comfort, but currently only consider the location of the interaction, like reaching for an XR Element, but not the performed interaction itself. Therefore, we built upon these valuable insights in this work but included the performed XR manipulation, i.e., translational and rotational movement, and their influence on users' comfort during mid-air gestures.

3 Methodology

We conducted a user study to examine the performance and comfort of different pinch-based mid-air input techniques for spatial direct
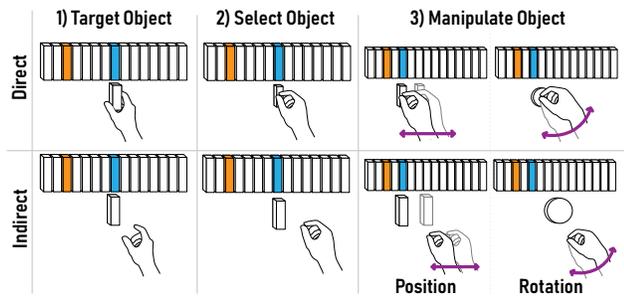
Figure 1: Point-and-Commit gesture: 1) the user targets an object by moving the hand close to it (*direct*) or pointing toward it (*indirect*); 2) performs a pinch to activate manipulation; and 3) moves or rotates the hand to set the value of the UI.

and indirect 3D manipulable XR User Interfaces (UIs). Based on related work, we define the following research questions:

RQ1 How does the interaction distance influence the user's preference to interact directly or indirectly for a more comfortable interaction?

RQ2 How does direct and indirect interaction influence comfort and performance?

RQ3 How does rotational and translational manipulation influence the perceived comfort and performance?

RQ4 How do the element direction, target, and granularity influence the comfort and performance?

3.1 Study Design and Task

We conducted a within-subjects experiment, where participants had to control positioning and rotational (3D Manipulation) XR UI elements with diverse levels of Granularity, i.e., the number of discrete steps available for each control element and set them to a predetermined value (Direction and Target). Higher granularity can increase the motor and cognitive effort required to complete a task accurately, and thus indirectly impact perceived difficulty. Participants used either spatially direct or indirect mid-air pinch gestures (Directness). Doing so, we followed the Point-and-Commit design concept for gestures. Users target digital objects using hand position and select them using a pinch gesture. During the interaction, the selected object will follow the pinching hand's pose. To end the interaction, the participant releases the pinch gesture (see Figure 1). Finally, we measured their influence on Comfort, Number of Interactions, Total Time, Convenience, Mental demand, and Physical demand.

3.2 Independent Variables

To gain a comprehensive understanding of the potential influences on performance and comfort during interactions with XR UI elements, we systematically manipulated the following six factors:

Directness We introduced the two levels *direct* and *indirect* interaction that embody contrasting approaches of spatial offset [5, 47]. For *direct* conditions, users engaged with the interface right at its visual representation. This imitates the interaction with non-virtual physical objects, where the user can only transform the

object when directly grasping it. In contrast, during *indirect* conditions, users were able to control the interface using their hand from any spatial location, e.g., with lowered hands not directly grasping the object and from a distance, see Figure 2. In both cases, users had to face their fingertips in the general direction of the virtual interface to select it with a pinch gesture. The *direct* conditions require the hand within the visual representation of the task, while the *indirect* conditions do not.

3D Manipulation Based on related work [7], we divided the user interaction in XR in two distinct 3D transforms: 1) *position*, and 2) *rotation*. These two motions are natural for the human arm and form the basis of most mid-air input in XR environments. We, therefore, integrated two user interface components in the form of a slider for positioning and a rotary knob for a rotational interaction, as depicted in Figure 1, representing one of the transforms each. This decision is based on related work. The slider was created with horizontal translation to avoid potential rapid shifts in perceived comfort and comfort associated with both vertical and diagonal translation [12, 18], which could artificially degrade the interaction experience compared to rotational interaction. The horizontal slider creates a baseline for translational interaction, combining good visibility and constant perceived comfort. The rotation knob has been designed to rotate around the fordinal axis, as previous work has shown the best accuracy results and comparable performance to rotation around the vertical axis [52]. However, rotations around the vertical axis are not widely applied, especially in User Interface designs. We, therefore, opted for rotation around the ordinal axis to balance visibility and perceived comfort. We used the same visualization above the respective element for both tasks to increase the comparability further.

Proximity To investigate the impact of the spatial separation between the user and the UI element, we examined four categories of proximity, denoted as 1) *close*, 2) *midway*, 3) *far*, and 4) *out of reach* [52, 63]. To keep the variation of reachable distances comparable across participants, we calibrated the distances based on the individual participants' arm length [52, 63]. The four levels were defined as follows: 1/2 arm length for *close*, 3/4 arm length for *midway*, one arm length *far*, and two arm lengths for *out of reach*. The *close* Proximity was further aligned with the length of the participant's lower arm, whereas the *far* Proximity corresponded to the extent of the full arm length. As such, the initial three levels explored the spatial domain within direct reach of the user's arm, while the interface during *out of reach* Proximity conditions examined user behavior beyond the personally reachable range, as depicted in Figure 2.

Granularity To assess the task performance and user comfort across varying levels of UI complexity and providing comparable Targets, we introduced three levels of interface Granularity: 1) *rough*, 2) *moderate*, and 3) *fine* (similar to [51]), to define the number of possible value steps that can be set for the given UI element by the participants. The *rough* Granularity level encompassed 13 potential steps, while the *moderate* level accommodated 19 possible steps, and finally, the *fine* level had 25 distinct steps. These divisions had multiple value steps across all Granularity levels at the same distance to the center, as depicted in Figure 2.4.

Target Following the Granularity, we further varied the target location, i.e., the distinct values on the UI element that participants had to select (cf. [51]). Therefore, we defined three Target locations equally distributed at 20%, 50%, and 80% of the respective Granularity. This results in the targets being located at the same spatial distance to the center for each level of Granularity. At the same time, the value steps between the targets increase by one for each level Granularity (see Figure 2).

Direction To assess the influence of abducting and adducting gestures movement, we varied the Direction in which the UI element needs to be manipulated. We introduced 1) *left*, and 2) *right* as distinct directions in which the Target was placed relative to the starting center position.

We systematically varied all five independent variables in a repeated measures design, totaling in 2 Directness × 4 Proximity × 2 3D Manipulation × 3 Granularity × 3 Target × 2 Direction = 288 *Conditions*. This also equals the number of trials per participant. Completing all tests took around 50 minutes.

Our independent variables can be grouped into two distinct groups. The first group defines the input technique, consisting of Directness and 3D Manipulation, and the second group represents the properties of the task, consisting of Granularity, Target, Direction and Proximity. To not confuse our participant with switching the interaction technique too often and to mitigate potential learning effects, we decided to counterbalance the sequence of the first group (Directness *x* 3D Manipulation) with a Balanced Latin Square (2 *x* 2 = 4 *Levels* repeated five times for 20 participants). The remaining factors of the second group (Granularity, Target, Direction and Proximity) were intentionally excluded from the Balanced Latin Square, streamlining the participants' attention and reducing modality switches. Within the Balanced Latin Square levels, we randomized the levels of Granularity, Target, Direction, and Proximity for each participant. This allowed participants to focus primarily on user input and avoid excessive modality shifts while at the same time conducting a questionnaire between each input technique (see subsection 3.3 for more details).

3.3 Dependent Variables

Comfort After each trial, participants were asked to assess their comfort level on a scale ranging from 0 (*very low*) to 10 (*very high*), based on the Borg-10 scale [6] as previously used in the related research [26, 52, 64]. This practical assessment method was chosen to avoid extended questioning using the NASA TLX, for example, which would have been extremely time-consuming and impractical given that our experiment has over 200 conditions. Further we chose to use Borg scale over metrics like the Consumed Endurance [18] or the Cumulative Fatigue [22, 59] as they do not take into consideration what the hand is doing or what gesture is being performed. Rather, they consider the arm's pose, which is comparable to our designed interactions. Using a Borg scale, we intentionally focus on the interaction rather than the posture.

Total Time The time elapsed between the appearance of the UI element and completion by the participant, indicated by the participant placing their hand in the resting zone (see subsection 3.5).

Number of Interactions A count of how many times participants interacted by grabbing the handle with the 3D Manipulation before finishing the condition.

Additionally, participants were asked on the following metrics, using 5-point Likert scales [42]:

Convenience Interacting with the system felt convenient.

Physical demand Interacting with the system was physically demanding.

Mental demand Interacting with the system was mentally demanding.

3.4 Study Setup and Apparatus

We developed a pair of XR UI elements, depicted in Figure 1. To represent *position* operations, we instantiated a discrete Slider design featuring a white handle for controlling the element, a blue value indicator, and an orange target-value highlighting. Participants moved the handle horizontally to change the value indicator. The handle movement translated 1:1 to the value indicator. Accordingly, *rotation* operations were implemented by a discrete Rotation-Knob design, once again with a white handle, blue value indicator, and an orange target-value indicator. To change its value, participants needed to rotate the handle around a user-facing axis for the *rotation* to change its value. To reach the outermost values of the element, participants had to turn the knob 180° counter-clockwise to get the most left value and 180° clockwise for the right one. Participants were asked to interact with the XR UI elements using the white handles, guided by the instruction to align the blue value indicator with the orange target-value indicator. Figure 1 shows both elements.

Our study setup consists of two applications: A VR application responsible for interacting with the 3D Manipulations on the Meta Quest Pro, and a desktop application for remote controlling, logging, and self-assessment of the participant's Comfort. Participants took a seat on a chair with no armrests at a table. Participants were allowed to rest their hands on the table during the experiment. The VR environment displayed an empty world with just the table in front of the user. The study operator could remote-trigger the display of the UI elements. The element was displayed in front of the user 25 centimeters below eye level. The white handles were roughly at shoulder height. Participants then interacted with the white handle using the instructed input technique of either *direct* or *indirect* input and *rotation* or *position* manipulation. Once participants completed their input, they had to place their hands on the table in a resting zone for 3 seconds to signal that they had concluded their trial and get some rest before continuing with the next element. Before that, however, the operator asked for the perceived Comfort and logged the respective value.

3.5 Procedure

After welcoming the participants, we introduced them to the experiment. We started by inquiring about any previous arm, shoulder, or back injuries, ensuring their capacity to participate in the study without compromising comfort or well-being. Once it was established that no injuries were present and participants expressed their willingness to participate, they were required to provide their consent through a formal agreement. After that, the participant's arm
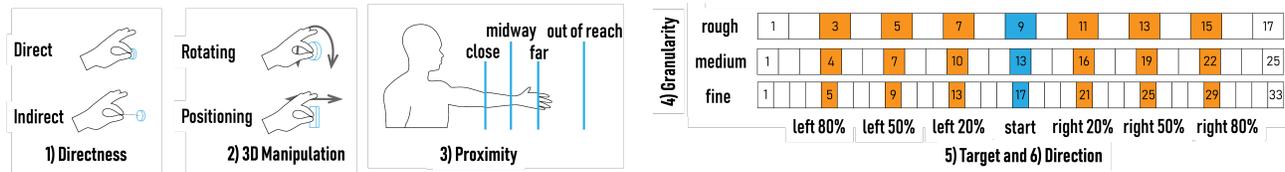
Figure 2: Overview of independent variables: 1) Directness; 2) 3D Manipulation; 3) four levels of Proximity relative to the participant's arm; 4) three Granularity levels; 5) Targets; and 6) Direction.

length was measured from the shoulder to the carpal. Participants were then introduced to the Meta Quest Pro device and how to interact within the virtual environment. Following a brief adaptation period to the virtual world, we launched our application on the glasses. Before starting the actual study, participants entered a training mode. This mode exposed all 3D Manipulations to the user and let them interact with either *direct* or *indirect*. Participants could freely test the input modalities and be accustomed to the look and feel of the 3D Manipulations.

Once participants had become comfortable with the interaction and had no further questions regarding the study's processes and input techniques, the operator deactivated the training mode, and the first trial was presented. Participants were granted the autonomy to approach the task as they deemed appropriate. No movement constraints were imposed, except that the participants must remain seated. When participants judged a task to be satisfactorily resolved, they placed their hands in a resting zone on the table in front of the user. While resting, participants communicated their comfort level. The subsequent task was presented after finishing the resting period. This sequence persisted until all trials were accomplished. When finishing a condition of the Balanced Latin Square, by changing either the 3D Manipulation or Directness, participants were asked to fill out a short questionnaire. After completing the questionnaire, participants continued to the subsequent condition in the Balanced Latin Square. Upon successfully concluding all trials, participants were requested to complete a demographics questionnaire, including their dominant hand preference. This questionnaire marked the conclusion of the experiment. On average, the entire experimental process spanned approximately 90 minutes. The study conforms to the ethical guidelines of the research institution.

3.6 Participants

We recruited twenty participants (five female, eleven male, four preferred not to say) between 21 to 37 years ($\bar{x}$ = 27.7, s = 5.2) through our university's mailing list and peer network. Five participants reported no prior XR experience, eight reported minimal, one reported medium experience, and six reported to be regular users. All participants confirmed the absence of musculoskeletal injuries or limitations of the arm and shoulder.

Participants voluntarily agreed to take part in the study and were free to withdraw from the study at any time without a reason. The collected data can be viewed by the respective participant at any time and deleted at request. No images, videos, or audio recordings were made during the user study to protect the user's privacy. Besides snacks and drinks, no compensation was provided.

Participants declared their willingness to participate in the user study by signing an informed consent form.

3.7 Analysis

We analyzed the collected data using a Repeated Measures ANOVA with 3D Manipulation, Direction, Proximity, Granularity, Target, and Directness as factors. We tested the data for the assumption of normality of the residuals and resorted to a non-parametric analysis in case of violations. We used Mauchly's test and corrected the results using the Greenhouse-Geisser method to test for violations of sphericity. When the Repeated Measure ANOVA reported significant effects, we conducted Bonferroni-corrected t-tests for post-hoc analysis. For the multi-factorial analysis of non-parametric data, such as Comfort and the *Questionnaires* for Convenience, Mental demand, and Physical demand, we performed an Aligned Rank Transform as proposed by Wobbrock et al. [66]. We used the ART-C procedure by Elkin et al.[11] for post hoc analysis. Further, we report the partial eta-square η_p^2 as an estimate of the effect size using Cohen's suggestions as small (> .0099), medium (> .0588), or large (> .1379) [10, 49]. For the count values of Number of Interactions, we fitted Poisson regression models and applied Type III Wald chi-square tests for significance testing.

4 Results

In this section, we report the results of the user study we conducted. Only significant results for improved readability will be reported in the text. Non-significant results for main- and interaction effects with up to three parameters are presented in the tables Table 1 to Table 3. Further results and post hoc tests can be found in the supplementary material.

4.1 Comfort

We assessed Comfort on a scale between 0 and 10 after each trial, and analyzed the data using the Aligned Rank Transform (Table 1) and fitted a Linear Effect Models with Directness, 3D Manipulation, Proximity, Granularity, Target, and Direction as predictors and participants as a random effect. To assess the significance, we used the Type III Wald F tests with Kenward-Roger df:

Directness The analysis revealed a significant higher comfort with a large effect size (η_p^2 = 0.48) for *indirect* (M = 7.12, SD = 1.92) compared to *direct* (M = 6.26, SD = 2.20) tasks.

3D Manipulation The analysis revealed a significant higher comfort with a large effect size (η_p^2 = 0.42) for *position* (M = 7.12, SD = 1.96) compared to *rotation* (M = 6.26, SD = 2.16) tasks.
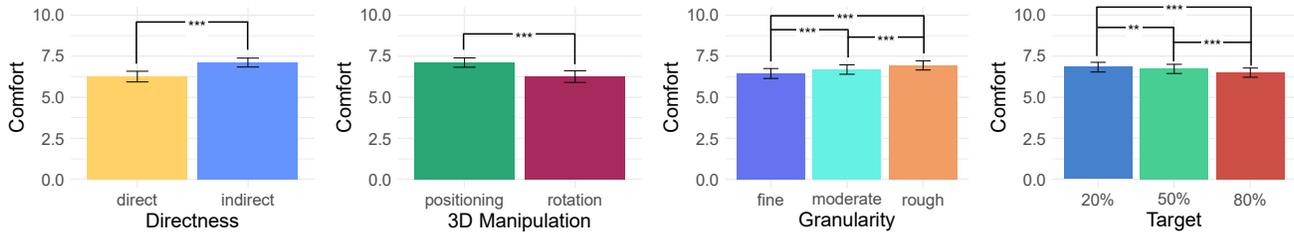
Figure 3: The Comfort measures for Directness, 3D Manipulation, Granularity and Target. The comfort was measured using the Borg scale. The error bars indicate the standard error.
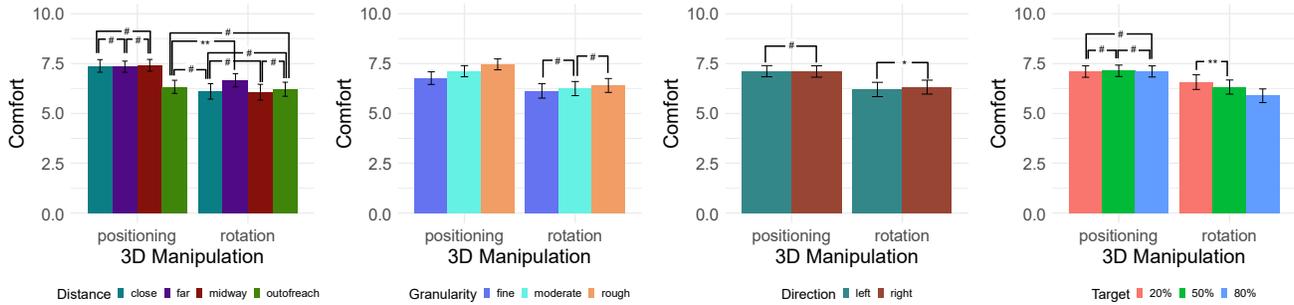

Figure 4: Interaction effects for Comfort. From left to right: 3D Manipulation and Proximity, 3D Manipulation and Granularity, 3D Manipulation and Direction, lastly 3D Manipulation and Target.The chart highlight all non-significant values # and significances other than < .001.

	Df	Df_{res}	F	p	Sign.
directness	1	5456	494.4321	<.001	***
distance	3	5456	53.832	<.001	***
manipulation	1	5456	470.3244	<.001	***
granularity	2	5456	49.8405	<.001	***
direction	1	5456	7.2755	.007	**
target	2	5456	30.171	<.001	***
directness x distance	3	5456	57.0176	<.001	***
distance x manipulation	3	5456	54.2698	<.001	***
manipulation x granularity	2	5456	10.7749	<.001	***
manipulation x direction	1	5456	5.8704	.015	*
manipulation x target	2	5456	28.1712	<.001	***
directness x distance x manipulation	3	5456	14.326	<.001	***
manipulation x direction x target	2	5456	5.5915	.004	**

Table 1: The Comfort analysis for all main and interaction effects with up to three variables. High residual degrees of freedom (Df_{res}) result from the within-subjects design: each of the 20 participants completed 288 trials. The ART ANOVA with Type III Wald tests computes contrasts across all repeated measures and six independent variables, leading to the expected high Df_{res} in this multi-factor repeated-measures context.

Proximity The analysis revealed a significant effect of Proxim-ity on comfort ratings with a large effect size ($\eta_p^2 = 0.26$). Post-hoc comparisons ($p < .01$) indicated that *far* tasks (M = 7.00, SD = 1.90) were rated significantly more comfortable than *close* (M = 6.74, SD = 2.06), *midway* (M = 6.74, SD = 2.07), and *out of reach*

(M = 6.27, SD = 2.31). Additionally, both *close* and *midway* were rated significantly higher in comfort than *out of reach* ($p < .01$). Finally, we found a significantly higher comfort between *close* and *midway* ($p < .01$).

Granularity The analysis revealed a significant effect of Gran-ularity on perceived comfort, with a large effect size ($\eta_p^2 = 0.41$). Post-hoc comparisons showed that comfort ratings differed signif-icantly between all levels: *fine* tasks were rated lowest in comfort (M = 6.45, SD = 2.13), followed by *moderate* (M = 6.68, SD = 2.07), and *rough* tasks received the highest comfort ratings (M = 6.93, SD = 2.10). All $p < .001$.

Target The analysis revealed a significant effect of Target on comfort ratings with a large effect size ($\eta_p^2 = 0.45$). Post-hoc com-parisons showed that 20% tasks (M = 6.83, SD = 2.09) were rated significantly more comfortable than both 50% (M = 6.73, SD = 2.09, $p < .01$) and 80% tasks (M = 6.50, SD = 2.14, $p < .001$). Additionally, 50% was rated significantly more comfortable than 80% ($p < .001$).

Direction The analysis revealed a significant effect with medium effect size ($\eta_p^2 = 0.06$) for a more comfortable *right* (M = 6.71, SD = 2.14) interaction compared to *left* (M = 6.66, SD = 2.07).

Interaction effects Several significant interaction effects were found. A notable interaction emerged between 3D Manipulation and Target ($F_{2.00,5456} = 28.17$, $p < .001$, large effect size $\eta_p^2 = 0.63$), as well as between 3D Manipulation and Proximity (large effect size $\eta_p^2 = 0.58$), both indicating strong combined influences on comfort ratings. Additionally, interactions were observed be-tween 3D Manipulation and Granularity (large effect size $\eta_p^2 = 0.33$) and between 3D Manipulation and Direction (large

IV	num Df	Df	F	p	sign.
Manipulation	1	17	11.594	.003	**
Granularity	1.860	31.612	7.934	.002	**
Target	1.859	31.602	50.423	<.001	***
Distance x Manipulation	2.589	44.007	16.397	<.001	***
Manipulation x Target	1.679	28.539	25.116	<.001	***
Granularity x Target	3.345	56.870	2.765	.045	*
Directness x Distance x Manipulation	1.820	30.937	3.515	.046	*
Directness x Granularity x Direction	1.849	31.440	5.163	.013	*

Table 2: The Total Time analysis for the main and interaction effects.

IV	Df	Df res	F	p	Sign.
Manipulation	1	19	13.008	.001	**
Directness	1	19	5.508	0.030	*
Manipulation x Directness	1	19	3.043	0.097	

IV	Df	Df res	F	p	Sign.
Manipulation	1	19	21.800	<.001	***
Directness	1	19	17.650	<.001	***
Manipulation x Directness	1	19	3.319	0.084	.

IV	Df	Df res	F	p	Sign.
Manipulation	1	19	6.434	0.020	*
Directness	1	19	4.550	0.046	*
Manipulation x Directness	1	19	0.001	0.986	

Table 3: The Convenience (left), Physical demand (middle) and Mental demand (right) analysis for the main and interaction effects.

effect size η_p^2 = 0.23), suggesting more nuanced comfort effects depending on task structure. Finally, a significant interaction was found between Directness and Proximity (large effect size η_p^2 = 0.27). Due to space considerations, the post hoc tests are reported in the supplementary material.

4.2 Total Time

We measured the Total Time participants needed to complete the task. See Table 2 and the following results:

3D Manipulation The analysis revealed a significant effect of 3D Manipulation on Total Time, with a large effect size (η_p^2 = 0.39). Post-hoc comparisons ($p < .05$) showed that *position* tasks were completed significantly faster (M = 8963, SD = 4416) than *rotation* tasks (M = 10508, SD = 5603).

Granularity The analysis revealed a significant effect of Granularity on total time, with a large effect size (η_p^2 = 0.29). Post-hoc comparisons showed that *rough* tasks (M = 9510, SD = 4926) were completed significantly faster than both *fine* (M = 9870, SD = 5067, $p < .01$) and *moderate* tasks (M = 9828, SD = 5305, $p < .05$).

Target The analysis revealed a significant effect of Target on total time with a large effect size (η_p^2 = 0.75). Post-hoc comparisons showed that 20% tasks (M = 9084, SD = 4707) were completed significantly faster than both 50% (M = 9665, SD = 5137, $p < .05$) and 80% tasks (M = 10458, SD = 5354, $p < .001$). Additionally, 50% tasks were completed significantly faster than 80% ($p < .01$).

Interaction effects Several significant interaction effects were observed for total time. Notably, there was a strong interaction between 3D Manipulation and Target (large effect size η_p^2 = 0.64), as well as between Proximity and 3D Manipulation (large effect size η_p^2 = 0.47). A weaker but still significant interaction was found between Granularity and Target (large effect size η_p^2 = 0.14).

4.3 Number of Interactions

We counted the Number of Interactions participants needed to finish the task. See Table 3 and the following results:

3D Manipulation Our analysis revealed a significant ($\chi^2(1)$ = 4.85, $p < .05$) effect for the 3D Manipulation. The post-hoc tests showed a significant lower Number of Interactions ($p < .0001$) for *position* (M = 2.39, SD = 0.92) and *rotation* (M = 2.76, SD = 1.45) tasks.

4.4 Convenience

We assessed the Convenience of the interaction on a 5-Point Likert Scale. See Table 3 and the following results:

Directness The analysis revealed a significant effect of Directness on perceived convenience, with a large effect size (η_p^2 = 0.22). Although both *direct* and *indirect* tasks received similar median ratings ($\tilde{x}$ = 4), post-hoc analysis ($p < .05$) showed that *indirect* was rated significantly more convenient than *direct*.

3D Manipulation The analysis revealed a significant effect of 3D Manipulation on perceived convenience with a large effect size (η_p^2 = 0.41). Post-hoc comparisons showed that *position* tasks ($\tilde{x}$ = 4) were rated significantly more convenient than *rotation* tasks ($\tilde{x}$ = 3, $p < .001$).

4.5 Physical demand

We assessed the Physical demand of the interaction on a 5-Point Likert Scale. See Table 3 and the following results:

Directness The analysis revealed a significant effect of Directness on perceived physical demand, with a large effect size (η_p^2 = 0.48). Post-hoc comparisons ($p < .001$) showed that *direct* tasks were rated as significantly more physically demanding ($\tilde{x}$ = 4) than *indirect* tasks ($\tilde{x}$ = 2).

3D Manipulation The analysis revealed a significant effect of 3D Manipulation on perceived physical demand, with a large effect size (η_p^2 = 0.53). Post-hoc comparisons ($p < .001$) indicated that *rotation* tasks were rated significantly more physically demanding ($\tilde{x}$ = 3.5) than *position* tasks ($\tilde{x}$ = 2).

4.6 Mental demand

We assessed the Mental demand of the interaction on a 5-Point Likert Scale. See Table 3 and the following results:

Directness The analysis revealed a significant effect of Directness on perceived mental demand, with a large effect size (η_p^2 = 0.19). Although both *direct* and *indirect* tasks had the same median
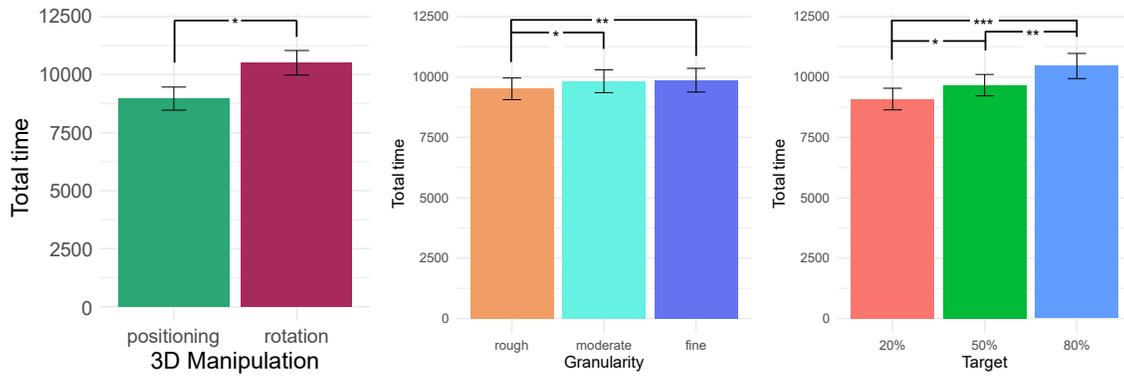
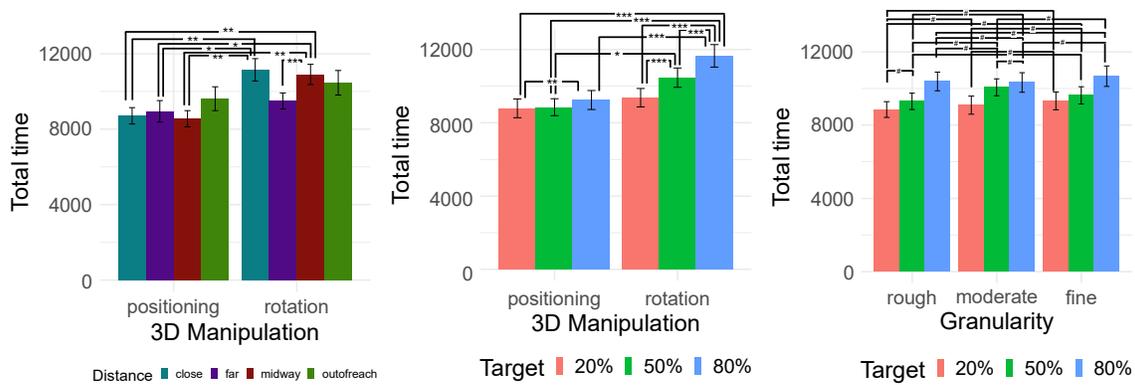Figure 5: The Total Time (in milliseconds) for 3D Manipulation, Granularity, and Target.

Figure 6: Interaction effects for Total Time (in milliseconds). From left to right: 3D Manipulation with Proximity, 3D Manipulation with Target, and Granularity with Target. For better clarity and visibility, the last chart highlights all non-significant values with #.
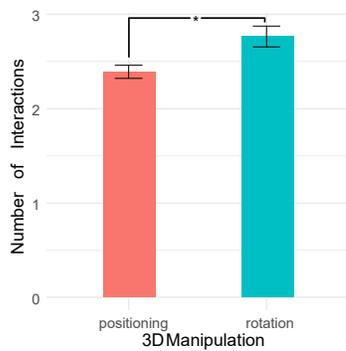

Figure 7: The Number of Interactions for 3D Manipulation.

rating ($\tilde{x} = 2$), post-hoc analysis ($p < .05$) showed that *direct* was perceived as significantly more mentally demanding than *indirect*. **3D Manipulation** The analysis revealed a significant effect of 3D Manipulation on perceived mental demand, with a large effect size ($\eta_p^2 = 0.25$). While both *position* and *rotation* tasks had

the same median rating ($\tilde{x} = 2$), post-hoc comparisons ($p < .01$) revealed that *rotation* was rated as significantly more mentally demanding than *position*.

4.7 Qualitative Feedback

After the study, we conducted a semi-structured interview to collect additional qualitative insights. We found that the input technique directly influences the perceived comfort, and most of our participants reported that they preferred to interact with the slider than the rotation knob [P1, P5, P13, P14, P17, P20]. Only a few participants mentioned the rotation knob as their favorite interaction ("In fact, rotation because it's precise and comfortable" [P4]). Most participants reported an increased comfort only when certain side conditions were met, like *indirect* interaction ("Rotation indirect was the most comfortable, as the hand could stay in place and setting the value was relatively simple" [P15]) or interacting with distant elements ("Rotating is quite nice, but not if the knob is so close to me. Only when it's far away" [P19]). While only one participant mentioned this, the interaction effect between *close rotation* and *far rotation* confirms the existence of this effect. However, we could not identify the same effect for the *out of reach* distance. Mostly,
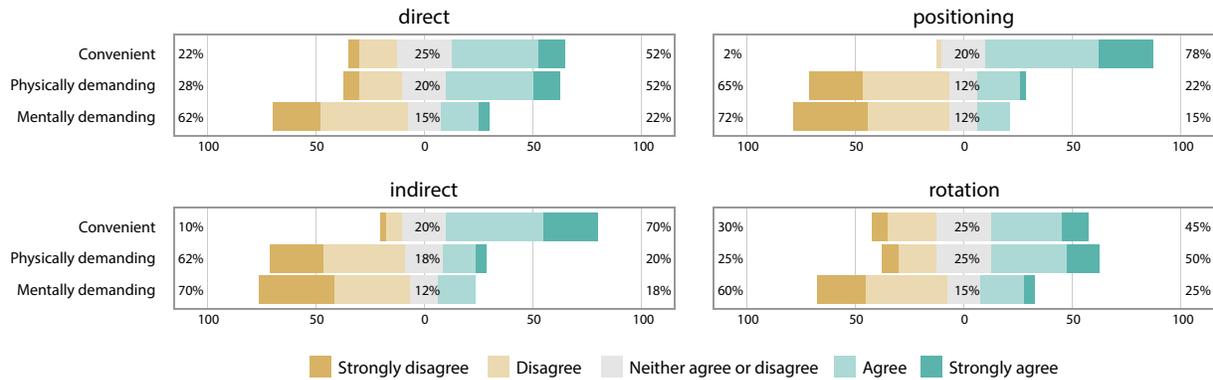
Figure 8: Left column shows the distribution of the likert scales for DIRECTNESS, at the top *direct*, at the bottom *indirect*. The right column displays the distribution for 3D MANIPULATION, at the top *position*, and at the bottom *rotation*

they preferred the possibility of resting their hand on the chair, lap, or table ("Indirect controls were great. Very pleasant because you could leave your arms on the armrest" [P17], "I liked indirect more than direct. I could rest my hand in the lap all the time. They mostly preferred not to finish the tasks faster using indirect input.
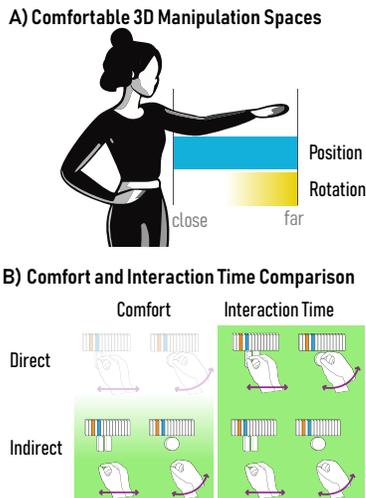
5 Discussion

Figure 9: A) Preferred 3D MANIPULATION for comfortable input: *rotational* match *positioning* elements for distant, fine-granular interactions. B) For comfort, indirect Manipulation is prefered, though it does not yield faster Interaction Times.

5.1 Allow for Indirect Interaction to Increase Perceived Comfort (RQ1, RQ2)

We found that the DIRECTNESS of the interaction **influenced the perceived comfort (RQ1)** but **not the actual performance (RQ2)**. Our participants overwhelmingly reported higher comfort

when using *indirect* interaction compared to *direct* one. This finding is backed by the COMFORT measurements, as well as by the post-study interview.

We attribute this effect to the postures participants took when interacting indirectly. During trials with indirect input, participants often rested their hands on their lap or table. This adds support to the arm and lowers the physical strain, increasing comfort. This is further backed up by higher scores for PHYSICAL DEMAND. Additionally, participants mentioned this behavior during the interview and the trials. When participants did not rest their arms on a surface during the interaction, they could still hold their arms lowered, increasing the comfort (see subsection 2.2).

We did not see a difference in performance. This can be explained by indirect and direct interaction requiring the same movement or motion to perform the input. To boost the performance of the interaction, designers need to consider different manipulation techniques rather than indirect information (see Figure 9).

Reflecting on our results, we found ample evidence that indirect interaction indeed increases comfort. However, our results indicated no increase in performance for indirect interactions. Based on these results, we suggest providing users with the option for indirect input, which increases comfort while not affecting the performance.

To answer **RQ1** *"How does the interaction distance influence the user's preference to interact directly or indirectly for a more comfortable interaction?"*, the results showed that the *indirect* interaction is more comfortable and should considered superior to *direct* interaction, see Figure 9. However, to answer **RQ2** *"How does direct and indirect interaction influence comfort and performance?"*, we did not find evidence of performance differences between the DIRECTNESS.

5.2 Prefer Position-Manipulation Over Rotation-Manipulation (RQ3)

Our results indicate an **decrease in perceived comfort for rotational 3D MANIPULATION compared to positioning 3D MANIPULATION (RQ3)**. Further, the TOTAL TIME needed to complete the tasks was lower when translating compared to rotating. This higher efficiency resulted in higher performance,

as users required less time to complete the task with equal outcomes. Finally, **translational interactions showed higher Convenience**, while at the same time **decreasing Physical demand and Mental demand**.

Compared to translational interactions, the increased discomfort of rotational interactions aligns with previous work [56]. However, it also highlights the necessity to consider not only postures like RULA [36] or the Consumed Endurance [18] but also the type of interaction to rate the perceived comfort. Looking closely at rotational interactions, we found comparable comfort scores throughout the reachable space and beyond. The manipulation is invariant to the interaction distance (RQ3). However, it is surprising that outside of the reachable area, the comfort score remains the same for rotation and approximates the same value for translation manipulation. Besides participants reporting the overall better comfort of rotational movements for further away interaction distances, we found no additional evidence or explanation for why this effect occurred. Another strange behavior is the peak of performance compared to all other lengths for far rotational manipulations. Rotational manipulation performs highly unexpected in the outer end of the arm reachable space and beyond. This should be further investigated in future work, as we cannot provide enough explanation of why these effects happen.

Further, we found that while rotational manipulation overall rates worse in comfort than translational manipulation, it does not suffer from significant drops in comfort when manipulating high-complexity elements. Yet, of note is that far-away rotational manipulations again decrease the comfort. Hence, short yet highly fine-granular rotational manipulations can still be comfortable (see Figure 9). We assume that this higher comfort for the rotational manipulation is caused by a better subtlety of rotating movements induced by the wrist than the shoulder for translation. It seems easier for users to rotate their hands than to move them precisely. This would make it easier to control the element right, thus increasing the perceived comfort.

Given these findings, we suggest focusing on translational interactions for future interfaces, where users must move their hands rather than rotate them. In some cases, like interactions far from the user, rotational manipulation becomes comparably comfortable. Yet, when high manipulation complexity is needed, interface designers should consider rotational manipulation. When using rotational interactions, we suggest allowing for indirect interaction or adapting the proximity of the interface element for pleasant and accurate interaction.

To answer **RQ3** *"How does rotational and translational manipulation influence the perceived comfort and performance?"*, our results suggest faster task completion times for translational movements and users reporting higher comfort and convenience ratings. At the same time, participants reported decreasing physical and mental demands, rendering the translational interaction superior to rotational ones. However, translational interactions require more space compared to rotational tasks. Therefore, adaptations in confined spaces facilitate higher comfort levels [37].

5.3 Direction and Target for Rotation Matters

Depending on the manipulation technique, the direction, and target showed an influence (**RQ4**). Rotational manipulation suffers from decreased comfort, and the more participants have to rotate to reach the target, the further the comfort decreases. This is because humans cannot continuously and indefinitely rotate their hands. The forearm supination and pronation allow for around 113° and 77° of the lower arm [56]. This limits the maximum reach users can comfortably rotate an object before regripping. This increases the task completion time and reduces performance and comfort.

Further, we found a significant impact on the rotation direction for rotational manipulation. Rotations to the right scored higher comfort levels. A possible reason for this can be found in the physiology of the forearm. The supination allows for a greater rotation (113°) than the pronation (77°) [56]. Therefore, right-handed humans can rotate their forearm further to the right side than the left, facilitating a more excellent range of motion and possibly explaining the slight preference to rotate to the right. Based on this, we suggest 1) using rotary interactions only for close targets and 2) prefer rotations to the right.

To answer **RQ4** *"How do the element direction, target, and granularity influence the comfort and performance?"*, keeping the interaction rough, granular, and minor in movement results in higher perceived comfort. We noticed a drop-off in comfort when participants had to move or rotate for the 50% and 80% targets. Also, the task's granularity plays a significant role in comfort. While the perceived comfort remains comparable throughout rotational movements, we have noticed a decrease when the translational movements become fine-grained. Finally, the element direction also influences the perceived comfort, with interactions to the right being preferred. However, this should be viewed cautiously, as the influence of handedness cannot be ruled out. Only right-handed persons were tested in our study.

5.4 Recommended Guidelines for Comfort-based Gesture Interaction

Based on related work and our findings, we these several guidelines for designing comfortable gesture-based interactions:

Variety of Gestures Repeating similar gestures frequently can reduce comfort due to muscle fatigue and altered posture [15, 16]. Alternating between gesture types, such as translational (straight-line movements) and rotational (twisting or turning movements), engages different muscle groups, mitigating fatigue. Although translational gestures are generally more comfortable, rotational gestures can be similarly comfortable within easy reach or when the arm is fully extended, providing a suitable alternative to prevent repetitive strain.[38]

Prefer Indirect Gestures Indirect gestures consistently offer higher comfort, aligning with established design guidelines [8]. However, contrary to prior findings suggesting indirect gestures are faster, we observed similar interaction times for direct and indirect gestures. Therefore, indirect gestures are recommended primarily for enhanced comfort, while direct gestures may suit brief, close-range interactions better.[3, 4]

Interchangeability of Direct and Indirect Gestures Both our study and recent guidelines confirm indirect gestures as more

comfortable [8]. However, performance differences between direct and indirect gestures observed in prior research were not replicated in our findings, indicating that further investigation is necessary. Ensuring direct gestures are interchangeable with indirect ones remains advisable for flexibility and comfort.[3, 4]

Proximity to the Human Body Keeping gesture interactions close to the user's body enhances comfort significantly, consistent with previous studies [52, 56]. Our research expands on this by showing rotational gestures maintain relatively consistent comfort across reachable space, matching the comfort of translational gestures at extended distances. Thus, rotational gestures offer viable alternatives for distant interactions without compromising comfort.[3]

Preference for Translational Gestures Translational movements are generally more comfortable and recommended as the primary gesture type [52, 56]. However, rotational gestures can be effectively interchanged with translational gestures in certain contexts to avoid fatigue, particularly in areas close to the body or fully extended arm positions.

6 Limitations and Future Work

Our results provide valuable insights into the comfort and performance of mid-air interactions. In the following, we discuss the limitations of our work and give directions for future work.

6.1 Internal and External Study Validity

We carried out a controlled experiment to investigate rotational and translational mid-air interactions in Extended Reality. However, it is essential to note that the outcomes found with a limited number of participants may not generalize to the entire population, especially considering the WEIRD [30] sample in our experiment.

Also, technical limitations of the Meta Quest Pro have to be considered due to tracking inaccuracies (e.g., due to different hand sizes or shapes [54]). Nevertheless, we decided to use the Meta Quest Pro instead of optical marker tracking because participants complained in pre-tests about the additional weight of the tracking markers on their fingers, resulting in increased fatigue and discomfort.

Besides the technical limitations, external factors, such as various physical characteristics, such as handedness or age-related changes to the musculoskeletal system, need to be investigated. For example, left-handed people are more skilled with working with their non-dominant hand than right-handed people [31]. This allows them to accumulate more rest time for their arms, as they can alternate more easily between the arms they use for interaction.

Further, this study used an abstract task design to compare translational and rotational interaction. The task design was carefully designed to be as comparable as possible. Yet, many variables are unexplored, such as the distance used for the translation, other interaction axes, continuous interaction, or UI Element design with different affordances. With this study, we established an exploration towards the comparison of these primitive gesture building blocks. These variables will be explored in more detail in future work to uncover more insights. Our work provides a solid foundation for further comparative exploration of translational and rotational interaction in XR.

6.2 Carry-Over Muscle and Mental Fatigue

While we instructed participants to rest between the conditions whenever necessary and enforced rest between trials, we must consider muscle and mental fatigue throughout all trials. Thus, we actively lowered carry-over effects for muscle fatigue by counterbalancing the interaction technique and mental fatigue with randomization of the task participants had to perform. We implemented a counterbalancing approach for the interaction technique to minimize potential carry-over effects related to muscle fatigue. Additionally, we addressed mental fatigue by randomizing the properties of the tasks participants had to perform.

6.3 Exploring Alternative Interaction Techniques

We used pinch-based gestures in this study. While pinch gestures are the most common interaction technique, alternative techniques regarding their impact on physical and mental fatigue remain unexplored. In future work, we will compare alternative interaction techniques, such as pointing or eye gaze, on the perceived physical and mental fatigue levels.

7 Conclusion

In this work, we examined the ergonomic foundations of mid-air interaction by focusing on translation and rotation, the primitive building blocks underlying XR gestures. Rather than proposing new techniques, we analyzed how these core transforms shape comfort across varying distances, directness, granularities, and targets. Our study shows that translational input is generally more comfortable and efficient, while rotational input can serve as a viable alternative in specific spatial or fine-granular contexts. Indirect interaction further reduces physical demand without affecting performance. Together, these findings offer a foundational understanding of comfort in mid-air manipulation and provide practical guidance for designing more ergonomic and sustainable XR interfaces, supporting future Augmented Human systems that depend on the symbioses between human and system through comfortable mid-air interaction.

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