Investigating the Effects of Haptic Illusions in Collaborative Virtual Reality

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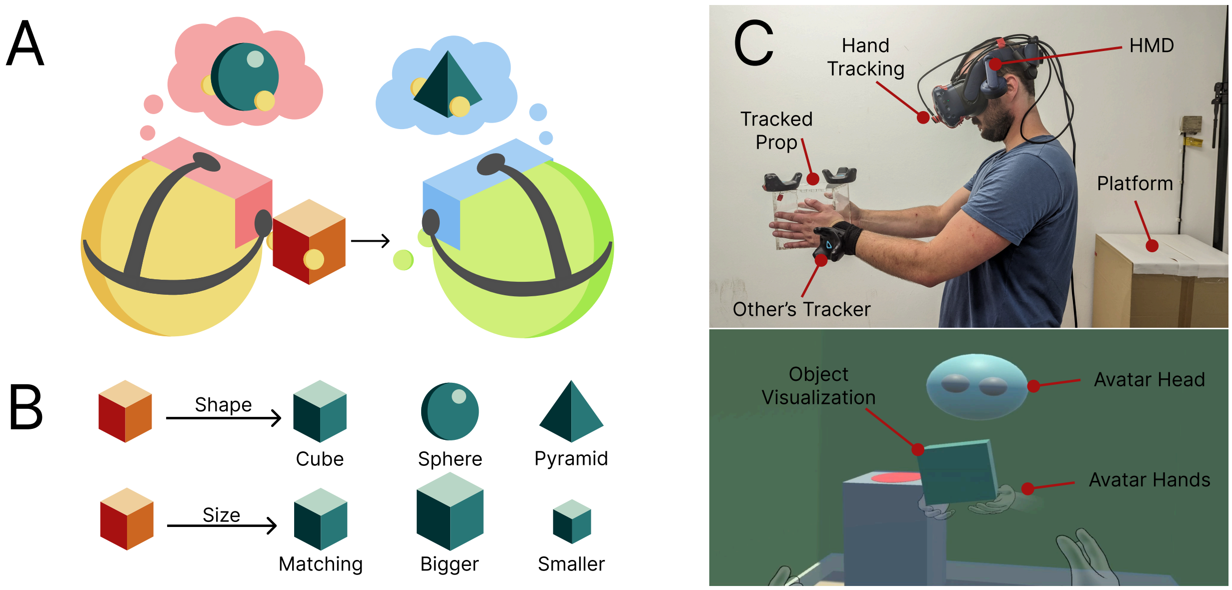

Fig. 1: In this work, we investigate how visual shape and size illusions influence users' performance, experience, and behavior during a collaborative task in VR. **A** illustrates the task setup from our user study, where participants were asked to hand over a physical object while we independently manipulated its visual shape or size in VR for each participant. **B** presents the different visual stimuli used across trials. In each trial, either the shape or the size of the object was altered independently for the two participants. **C** depicts the physical setup (top) and its corresponding virtual environment (bottom). The setup included two head-mounted displays equipped with hand tracking and a physically tracked prop. In VR, participants saw virtual representations of their partner's head and hands, along with the manipulated object.

Abstract— Our sense of touch plays a crucial role in physical collaboration, yet rendering realistic haptic feedback in collaborative extended reality (XR) remains a challenge. Co-located XR systems predominantly rely on prefabricated passive props that provide high-fidelity interaction but offer limited adaptability. Haptic Illusions (HIs), which leverage multisensory integration, have proven effective in expanding haptic experiences in single-user contexts. However, their role in XR collaboration has not been explored. To examine the applicability of HIs in multi-user scenarios, we conducted an experimental user study (N=30) investigating their effect on a collaborative object handover task in virtual reality. We manipulated visual shape and size individually and analyzed their impact on users' performance, experience, and behavior. Results show that while participants adapted to the illusions by shifting sensory reliance and employing specific sensorimotor strategies, visuo-haptic mismatches reduced both performance and experience. Moreover, mismatched visualizations in asymmetric user roles negatively impacted performance. Drawing from these findings, we provide practical guidelines for incorporating HIs into collaborative XR, marking a first step toward richer haptic interactions in shared virtual spaces.

Index Terms—haptic illusions, multi-user collaboration, virtual and extended reality

1 Introduction

From shaking hands to handing someone a tool to lifting bulky furniture; our sense of touch is crucial in everyday interpersonal communication and collaboration. However, when working together in extended reality (XR) environments, this haptic aspect of collaboration is lost, as XR systems primarily rely on simple vibration feedback from hand-held devices, which cannot reproduce the wide range of haptic feedback we experience in real-world interactions [28]. While research has brought forth many approaches to enrich haptic feedback in XR – including grounded encounter-type systems [34, 35] as well as hand-held [9, 13] or wearable [40] devices – these systems are generally either limited to produce haptic feedback for one user at a time or require both users to wear or hold the device constantly, severely restricting the possible collaborative interaction between them. Consequently, most approaches to delivering realistic haptic experiences in collaborative settings rely on integrating physical proxy objects that can be picked up, placed, or handed over among users [12, 25]. While these passive props offer high-fidelity information regarding the specific geometric and

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material features they were designed to represent, they cannot adapt these properties, which severely limits the range of haptic experiences they can provide.

Haptic Illusions (HIs) have been shown to enrich and extend the spectrum of haptic feedback which can be delivered by passive props [30]. Sensory illusions, including HIs, leverage the interconnected relations of sensory modalities in creating our unified perception [19], which enables one sense, such as vision or audition, to influence and partially overwrite another, such as our haptic sense. This multisensory integration can be exploited by deliberately manipulating presented visual or auditory cues during interactions. Previous research has shown these manipulations to be effective in altering the perceived geometric features – e.g., shape [48] and size [3] – and material properties – e.g., temperature [24], stiffness [56], weight [43], and surface texture [20] – of physical objects. They achieve this by manipulating the visual or auditory presentation of the objects [3, 20, 24, 48] or their behavior during interactions such as pressing [56] or lifting [43].

However, prior XR research solely focused on the effects of HIs on single users, overlooking their possible influence on collaborative settings, where users need to interact with one another and physical props may need to be shared. In these settings, HIs can enable the same physical props to represent different digital objects for each user, leading to divergent perceptions of properties such as size or shape. In addition to extending the range and adaptability of haptic feedback, this also enables novel opportunities for individual personalization of haptic experiences for each user, for instance, to help balance collaborative trainings [1, 45] and competitive games [23, 29, 39] based on competency levels, or increase accessibility through personal haptic calibration. However, when users attempt to share and hand over these manipulated props, these mismatches may cause coordination errors, disrupt interaction flow, or result in physical discomfort.

To address these potential challenges, we investigate the impact of HIs on multi-user collaboration in co-located XR environments. Specifically, this work investigates how visual manipulation of objects' shapes and sizes affects users' experience, performance, and behavior in a collaborative handover task in Virtual Reality (VR). For this, we conducted an experimental user study (N=30) with pairs of participants who were tasked to hand over a physical object between them while we varied the visual shape or size in their individual representations. Using a mixed-methods approach, we found that visuo-haptic mismatches consistently degrade both task performance and user experience, even when users actively adapt by shifting sensory reliance and employing mitigation strategies. Moreover, mismatched visualizations between users can have an even greater impact on performance than visuo-haptic discrepancies alone, with the extent of this effect varying depending on user's role in the interaction. Derived from our quantitative and qualitative findings, we propose guidelines for integrating HIs into collaborative XR contexts. With this work, we provide a foundational step toward enabling richer, more seamless haptic experiences in collaborative XR facilitated through HIs, paving the way for more natural and effective collaboration in shared virtual environments.

2 Related Work

This work draws from a large body of research relating to haptics and collaboration in XR. In the following, we provide an overview of conventional haptic rendering techniques (subsection 2.1), their use in collaborative XR systems (2.2), and the potential of HIs in these contexts (2.3).

2.1 Active Haptic Rendering

Producing realistic haptic feedback is one of the key challenges in current immersive systems [52]. Haptic perception is complex, comprising both kinesthetic as well as cutaneous cues, such as pressure, vibration, and thermal sensations [27]. While current state-of-the-art devices rely on vibrotactile feedback in hand-held controllers to offer basic feedback, these systems do not suffice to fully reproduce the intricacies of haptic experiences we are presented with when interacting with our natural surroundings [27, 28]. To address this, research has developed numerous approaches to deliver more realistic haptic sensations to single users. High-resolution robotic devices – such as the PHANToM [35], Omega[1], or Falcon [34] – produce precise forces at high-frequencies while the user is holding their end-effector. Encounter-type haptic systems [36] trade this precision and speed to eliminate the requirement for constant contact and an increased working area. However, both approaches require bulky systems, which can only generate haptic sensations for a single user at a time. Hand-held devices [9, 13] and wearables [40] offer more mobility and may be distributed to several users. However, these systems still obstruct or constrict the users' hands. This confines interaction and feedback to the single device, limiting its suitability for collaborative settings where users may need to interact with shared objects or each other.

Overall, while conventional haptic rendering techniques have proven effective for specific single-user tasks, they do not easily translate to multi-user settings, necessitating alternative approaches for collaborative XR.

2.2 Passive Haptics in Collaborative XR

Collaborative XR systems are becoming more prevalent and mature, particularly with the advancement in augmented and mixed reality enabling novel opportunities for co-located cooperation [17]. While conventional haptic approaches are used to support remote cooperation [51], they are largely inadequate for co-located collaboration. Social games and Computer Supported Cooperative Work (CSCW) in XR consequently predominantly either provide no haptic feedback or rely on physical props placed in the environment. These comprise hand-held passive props for each user – such as sports rackets and sticks [29, 39] or swords to safely hit each other [23] – as well as prefabricated objects spread on a table [25,42] or around the environment [12,16], with which all users may physically interact. Single-user studies showed passive physical props to improve task performance [57], presence [26,57], and spatial orientation [26]. To extend the perceived interaction space while still allowing passive props to be touched, some approaches employ redirected walking techniques on multiple users [4, 15, 16, 37]. With subtle manipulations (e.g., rotations) of the virtual scene, these manipulate users' walking trajectories, which is used to avoid collisions [15] while still allowing for users to interact with physical objects [16] or each other [37].

The integration of passive props offers realistic shared haptic experiences with the potential to represent predefined geometric and material characteristics with high fidelity. However, they are not able to dynamically adjust their properties, severely limiting their versatility regarding haptic feedback as well as potential applications. HIs offer a potential approach to extend the range of haptic feedback these physical props can offer without requiring additional complex hardware.

2.3 Haptic Illusions

When exploring our physical environment, we naturally rely on multiple senses, leading to crossmodal interactions that shape our perception. Sensory illusions, such as HIs, emerge when conflicting information is presented across different sensory modalities, shifting subjective perception toward a unified interpretation of the stimuli [19]. This integration can be exploited to generate altered haptic sensations by deliberately inducing mismatches in presentation, e.g., through modifying visual or auditory cues during object interactions. Prior research has shown these approaches to efficaciously alter the perceived geometry – e.g., shape [48] and size [3, 48] – and material properties – such as stiffness [56], weight [43], temperature [24], and surface texture [20] – of interacted objects (see [30] for a comprehensive overview). Focusing on illusions targeting shape or size manipulations, numerous works have shown that physical proxy objects, coupled with discrepant visual representations in Augmented Reality (AR) or VR, can suffice to render the sensation of a large variety of virtual object shapes and sizes [31, 46, 47]. In a psychophysical experiment, Tinguy et al. [48] investigated the degree to which visual and haptic objects may mismatch in VR without users being able to detect it. They showed that changes

[1] https://www.forcedimension.com/products/omega, accessed: 2025-03-25

in object widths below 5.75% remain imperceptible, while changes in the surface's angle and curvature may change up to 43.8% and 66.66%, respectively, before being detected. Further, Auda et al. [3] showed that offsetting hand representations in VR while grabbing physical objects can extend the effective range of allowed size mismatches. Analogously, Ban et al. [6, 7] showed that visually distorting hand poses during grasping allows for alterations of objects' perceived shape.

While the large body of prior research into HIs shows the potential benefits of integrating these illusions with passive tangible props to enrich the haptic experience, they solely investigated HIs impact in single-user scenarios. The benefits and drawbacks of HIs for collaborative settings, which rely on passive props the most, have been scarcely considered: In an analog setting, Lefebvre et al. [33] applied HIs on a tabletop display, which allows anyone currently interacting with the table to feel a deformation effect. For collaborative interactions, Argelaguet et al. [2] showed the potential of visually discriminating the stiffness of a virtual object in tandem while both users interact on separate tablet touchscreens.

Yet, the use of HIs for collaborative XR – where passive haptics are the most prevalent – remains unexplored. To address this gap, we investigate the impact of HIs in a multi-user collaborative VR task. By exploring the challenges of integrating HIs into multi-user contexts, we offer initial insights toward enabling richer and more dynamic haptic experiences in collaborative XR to support user communication and interaction.

3 Study Design

We conducted an experimental user study to explore how HIs affect user experience, performance, and behavior in multi-user collaboration. Specifically, we examined how visuo-haptic illusions that alter an object's shape and size influence a handover task in VR. We used a repeated-measures design, varying the virtual shape or size of the object for each participant individually during the handover task, as presented in Figure 1A. We decided to implement drastic changes rather than gradual differences to ensure a clear perception of the manipulations and to explore how significant mismatches between the real and virtual worlds affect the handover process. With this, we aim to address the research questions: (RQ1) How does the introduction of individual visuo-haptic mismatches of an object's shape and size influence performance and user experience in a collaborative handover task in VR? (RQ2) How do users adapt to these discrepancies in visuo-haptic and interpersonal presentation?

3.1 Task & Stimuli

We paired participants in teams of two. In each trial, one person picked up a physical object from a platform on their side of the room and handed it to their partner, who then placed it onto another platform. After they completed the placement and returned to their starting positions, participants were prompted to answer a short questionnaire displayed in the virtual environment regarding their subjective experience. Afterward, the next trial began; this time, the opposite participant was grabbing and handing over the physical object. There was no time limit for the handover.

In each trial, we varied the visualization of the object for the targeted participant (**Vis**), the visualization of the object for the opposing participant (**OthersVis**), and the role of the participant in the handover (**Role**):

Vis: Depending on the trial, we visually varied either the shape or the size of the virtual object. An overview of the changes introduced is presented in Figure 1B. For the Shape-Condition we decided to use the basic geometric primitives that differed in local orientation and curvature (c.f. [48]) and displayed either a (1) *Cube*, (2) *Sphere*, or (3) *Pyramid*. The virtual cube matched the dimensions of the physical one exactly. For the others, we respectively fitted the diameter of the sphere and the base of the pyramid to the physical cube.

For the Size-Condition we displayed a cube of different sizes. Previous work showed that props can effectively represent virtual objects up to 50% larger than their actual size [3]. Based on this, we chose the following sizes for our experiment: (1) *Matching* the physical cube ($15cm \times 15cm \times 15cm$), (2) *Bigger* ($\times 1.5 \widehat{=} 22.5cm$), or (3) *Smaller* ($\div 1.5 \widehat{=} 10cm$).

OthersVis: Concurrent to varying the visualization of the respective participant, we also always varied the virtual object for the opposing participant. We use the same possible shapes or sizes as in Vis. We did not mix shape and size manipulations and only varied either the shape or the size for both participants, depending on the trial.

Role: The participant's role in the handover could either be the Giver or Receiver of the object. The roles were switched after each trial.

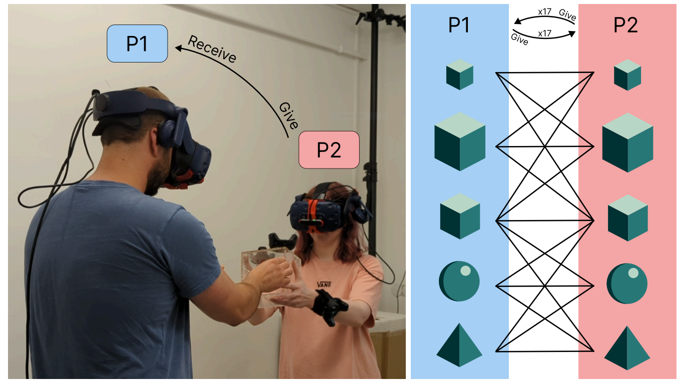

Fig. 2: Visualization of a single handover trial (left) and all combinations of Vis, OthersVis, and Role that we investigate (right).

The combination of all variables resulted in 18 conditions for the Shape-Condition (3 Shape× 3 OthersShape× 2 Role) and 18 conditions for the Size-Condition (3 Size× 3 OthersSize× 2 Role). As both conditions share two situations where the visual and physical objects match completely (once as Giver & once as Receiver), we removed these duplicate conditions. This resulted in a total of 34 trials for each study session, which are displayed in Figure 2. We randomized the trial order for each session.

3.2 Measurements

For each trial, we recorded the task completion time of the handover. To make sure we do not discard any possible effects of visualization on approach behavior, we measured the time from task start (participants in center position) to task end (participants return to center post-handover). Further, we collected subjective ratings from each participant on six task-related statements (see subsection 4.2), using a 7-point Likert scale (1 = *strongly disagree*, 7 = *strongly agree*). While collaborative VR experiences are influenced by various broad factors such as presence, involvement, and social connectedness, these are often shaped by complex interpersonal dynamics beyond the scope of our manipulation. Instead, we focused on aspects directly related to the interaction, task performance, and visuo-haptic presentation. Additionally, we audio-recorded the handover process to investigate communication strategies. For additional qualitative insights, we allowed participants to freely make comments at the end of each trial and conducted a semi-structured interview at the end of the study.

3.3 Apparatus

The physical and virtual setup for the study is displayed in Figure 1C. For participants to freely move around, we set up our experiment in an area of $\sim 4.1m \times 1.9m$. We placed two cardboard boxes in diagonal corners of this area (back-left and front-right corners) to serve as platforms. They were $50cm \times 50cm$ wide and $102cm$ high. We marked participants' starting points in the center of our area, spaced $108cm$ apart along the long axis. We created a virtual environment using

Unity3D[2] and displayed it in two HTC Vive Pro 2[3] Head-Mounted Displays (HMDs) sharing the same tracking space. The applications ran on two desktop PCs[4]. To track and display participants' hand movements, we mounted an Ultraleap Leap Motion Controller 2[5] on each HMD. For participants to see each other in the virtual environment, we integrated network synchronization using Photon Fusion 2[6]. We re-calibrated the position of both HMDs before every session. Additionally, we attached VIVE Trackers[7] to the left arms of participants tracked by the HMD of the respective other for increased precision in determining hand positions. For the handover task, we built a $15cm \times 15cm \times 15cm$ cube out of transparent acrylic glass and connected two VIVE trackers to the top in opposing corners. The entire passive prop, including trackers, weighed 1048 grams.

The virtual scene consisted of a minimal walled room with the dimensions of the physical interaction space. The participants' hands were represented as transparent outlines provided by Ultraleap. Because the generated changes in shape or size would cause the hands of participants to clip into or hover above the virtual object when handling the physical object, we employed hand redirection (cf. [5, 58]) to mitigate these mismatches. When participants reached out to grab the object from a platform or the other person, we broke the one-to-one mapping of real to virtual hand movements and subtly displaced the visual hand models. We used linear interpolation to adjust the virtual hands, ensuring they touched the virtual object at the same time and place as the real hands touched the physical object. The opposing participant saw the same adjusted hand representations. Additionally, they were presented with a virtual avatar consisting only of spheres for the head and eyes, thus only giving information about the other's head rotation in addition to their hand movements. The platforms were virtually displayed with the same dimensions, with small indicators on top showing where to place the physical object. We displayed our questionnaire directly in the virtual environment, where participants could interact with them using their free hands.

3.4 Procedure

After welcoming the participants, we informed them about the task, the study's objective, and our data processing procedure. We then asked them to sign a consent form. Each participant then filled out a questionnaire regarding their demographics, previous experience with VR, and familiarity with the other participant in their joined session. Afterward, we helped them put on the VR headsets and let them run through a short training phase consisting of three complete trials of the handover task and the subsequent survey. These three trials involved handling (1) a matching object, (2) an object of a different size, and (3) an object of a different shape. After ensuring that participants understood their task, we started the experimental trials. Upon finishing all trials, we helped participants remove their headsets. We then invited both participants to a voluntary semi-structured interview where we asked them to reflect and comment on their experiences, which was audio-recorded and transcribed.

3.5 Participants

We recruited 30 participants through university mailing lists. 17 participants described themselves as female and 13 as male. Participants' age ranged from 18 to 71 ($M = 26.70, SD = 8.94$). 29 were right-handed, and one was left-handed. 23 participants had experienced VR before (8 below 2h, 12 between 2h and 20h, and 3 for more than 20h). Participants had normal or corrected-to-normal vision[8] and no known conditions affecting the haptic acuity of their hands. Participants took part in the study as pairs of two. Two of the 15 pairs described themselves as friends, while the remaining had not met before. We offered participants 15€ or university course credit as compensation. Our institution's ethics board approved this study.

3.6 Data Analysis

To analyze participants' task completion times (TCT), we fitted Generalized Linear Mixed Models (GLMMs) with a Gamma distribution and a *inverse* link function using the Laplace approximation implemented in the `lme4` R-package [8]. Because completion times are the same for both participants of a session, we analyzed the data on a session rather than participant basis. For the SHAPE-CONDITION, we included the SHAPE of the GIVER, SHAPE of the RECEIVER, and their interactions as fixed effects. For the SIZE-CONDITION, we included the SIZE of the GIVER and RECEIVER, and their interaction as fixed effects. For both SHAPE-CONDITION and SIZE-CONDITION, we account for variability between participant groups by adding the unique session IDs as a random effect. Additionally, we account for learning effects by adding the trial index as another random effect.

For participants' ordinal ratings (of our subjective statements 1-6), we used Cumulative Link Mixed Models (CLMMs) with logit link functions. The models were fitted with the adaptive Gauss-Hermite quadrature approximation with 10 quadrature points, implemented in the `ordinal` R-package [14]. For the SHAPE-Condition, we included SHAPE, ROLE, OTHERSSHAPE, and their interactions as fixed effects. For the SIZE-Condition, we used SIZE, ROLE, OTHERSSIZE, and their interactions. For both, we added the participants' unique IDs as a random intercept to account for interpersonal variability.

For both the TCT and subjective ratings, we performed likelihood ratio tests (LRTs) comparing each model to reduced models, in which we individually dropped one fixed effect or interaction. Where we found a significant main or interaction effect, we conducted pairwise post-hoc comparisons with Bonferroni correction.

For qualitative analysis, we first transcribed the post-experiment interviews and participant comments during the study using Whisper[9] and manually corrected transcription inaccuracies. We used thematic analysis to identify themes in the interviews following the process outlined by Blandford et al. [10]. Three researchers independently coded the same three interviews (= 20%) using an open-coding approach. These codes were then discussed, and all researchers agreed on a final set of codes. Finally, one researcher coded all interviews (including re-coding of the three initial samples) with the defined codes using the Atlas.ti analysis software[10].

4 RESULTS

In the following, we present the results of our experimental user study. First, we report our quantitative results regarding task completion times (see section 4.1) and participants' subjective ratings (4.2) for both the SHAPE and SIZE conditions. We follow this with the qualitative findings from the post-experiment interviews (4.3).

4.1 *Task Completion Time*

For the SHAPE-CONDITION, LRTs revealed a significant main effect of the SHAPE of the RECEIVER ($\chi^2(6) = 14.70, p < .05$) on task completion times, but no significant effects of the GIVER's SHAPE ($\chi^2(6) = 10.68, p = 0.10$) or interaction effect between them ($\chi^2(4) = 6.07, p = 0.19$). Post-hoc comparisons on levels of the RECEIVER's SHAPE show significantly ($p < .05$) higher completion times for the *Pyramid* visualization ($M = 41.5$s, $SD = 13.0$s) compared to *Cube* ($M = 38.7$s, $SD = 16.0$s). The *Sphere* ($M = 38.8$s, $SD = 8.21$s) performed slightly worse than *Cube* and better than *Pyramid*, but these differences were not significant. Comparing the full model to a reduced

[2] Version 2022.3.3, https://unity.com/, accessed: 2025-02-25

[3] https://www.vive.com/us/product/vive-pro2/overview/, accessed: 2025-03-10

[4] PC1: Ryzen 9 7900X3D processor, 64GB RAM, NVIDIA RTX 4080 Super graphics card; PC2: Intel Core i7-6700K processor, 16GB RAM, NVIDIA GeForce GTX 1080 graphics card

[5] https://leap2.ultraleap.com/products/leap-motion-controller-2/, accessed: 2025-02-26

[6] https://doc.photonengine.com/fusion/v2/, accessed: 2025-03-10

[7] https://www.vive.com/us/support/wireless-tracker/category_howto/about-vive-tracker.html, accessed: 2025-03-10

[8] One participant noted a deficiency in their right eye but confirmed they could complete the task without difficulty.

[9] https://github.com/openai/whisper, accessed: 2025-03-10

[10] https://atlasti.com/, accessed: 2025-03-10

Question	VIS		OTHERSVIS		ROLE		V×OV		V×R		OV×R		V×OV×R	
	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p
SHAPE														
Q1	307.57	< **.001**	7.25	0.84	4.14	0.90	6.06	0.64	2.95	0.82	3.13	0.79	2.64	0.62
Q2	89.69	< **.001**	6.52	0.89	3.32	0.95	5.37	0.72	3.01	0.81	2.56	0.89	1.95	0.74
Q3	123.07	< **.001**	10.07	0.61	6.03	0.74	9.20	0.33	4.39	0.62	4.28	0.64	4.10	0.39
Q4	45.53	< **.001**	8.09	0.78	4.24	0.90	6.85	0.55	1.82	0.94	1.36	0.97	0.74	0.95
Q5	433.05	< **.001**	3.37	0.99	3.22	0.95	3.12	0.93	2.96	0.81	1.53	0.96	1.51	0.82
Q6	174.68	< **.001**	3.35	0.99	3.55	0.94	3.19	0.92	3.41	0.76	3.13	0.79	3.07	0.54
SIZE														
Q1	185.35	< **.001**	4.99	0.96	1.82	0.99	4.59	0.80	0.99	0.99	0.98	0.99	0.83	0.93
Q2	54.61	< **.001**	7.76	0.80	6.57	0.68	3.81	0.87	3.50	0.74	4.48	0.61	1.44	0.84
Q3	76.91	< **.001**	7.73	0.81	9.42	0.40	5.82	0.67	7.40	0.29	4.59	0.60	4.02	0.40
Q4	16.18	0.18	12.38	0.42	9.69	0.38	9.26	0.32	7.09	0.31	9.20	0.16	6.75	0.15
Q5	179.43	< **.001**	3.76	0.99	5.98	0.74	3.38	0.91	5.24	0.51	2.42	0.88	2.24	0.69
Q6	94.65	< **.001**	5.35	0.95	4.43	0.88	4.20	0.84	2.23	0.90	1.26	0.97	1.24	0.87

Table 1: Likelihood Ratio Tests comparing the full models to reduced models with one term or one interaction dropped out. Each column represents a model comparison, where VIS, OTHERSVIS, and ROLE are main effects, and the remaining columns are interaction effects. For example, VIS shows the difference between the full model to the model with the term VIS removed, and V×R shows the difference between the full model and a model with the interaction between VIS and ROLE removed.

one without a trial index as a random intercept, we found a significant difference in TCT ($\chi^2(1) = 120.59, p < .001$), suggesting a strong learning effect.

For the trials where SIZE was varied (SIZE-CONDITION), the LRTs revealed a significant main effect of the GIVER's SIZE ($\chi^2(6) = 17.89, p < .01$), RECEIVER's SIZE ($\chi^2(6) = 22.15, p < .01$) and a significant interaction effect of GIVER's and RECEIVER's SIZE ($\chi^2(4) = 15.94, p < .01$). Due to the involvement of interactions, we performed post-hoc comparisons on all groups of GIVER's SIZE×RECEIVER's SIZE and found the group *Matching* → *Bigger* ($M = 41.8$s, $SD = 16.9$s) performing the worst, resulting in significantly ($p < .05$) higher completion times than the groups of *Matching* → *Matching* ($M = 35.9$s, $SD = 8.74$s) and *Bigger* → *Matching* ($M = 37.8$s, $SD = 6.83$s). Additionally, we again found a learning effect with the LRT showing a significant difference between the models with and without the trial index as a random effect ($\chi^2(1) = 81.48, p < .001$).

4.2 Subjective Ratings

All Likelihood Ratio Tests comparing the full and reduced models are shown in Table 1. For the SHAPE-CONDITION, we found a significant main effect of SHAPE on all subjective ratings, while OTHERSSHAPE, ROLE, or their interactions did not show any significant differences when removed from the full model. Rating distributions for levels of SHAPE averaged over OTHERSSHAPE and ROLE are presented in Figure 3, with asterisks and brackets indicating significant differences found among groups with post-hoc comparisons.

For the SIZE-CONDITION, LRTs showed a significant effect of SIZE for all ratings except Q4 (*I think the other person performed their task well.*), and no other main or interaction effect. We present the average rating distributions in Figure 4. Significant differences among groups are again highlighted with an asterisk.

In the following, we present the results of post-hoc comparisons conducted on the main effects of SHAPE and SIZE in their respective conditions for each subjective rating.

4.2.1 *The interaction with the object felt natural.*

SHAPE-CONDITION For participants' assessments of naturalness of the interaction, post-hoc tests revealed significant ($p < .001$) differences among all levels of SHAPE, with *Cube* ($M = 6.08, SD = 1.01$) receiving the highest ratings, followed by *Sphere* ($M = 4.11, SD = 1.83$) and lastly *Pyramid* ($M = 3.54, SD = 1.79$).

SIZE-CONDITION Analogously, we found significant ($p < .001$) differences for all contrasts of SIZE, with *Matching* ($M = 5.96, SD = 1.12$) receiving the highest ratings, followed by *Bigger* ($M = 5.28, SD = 1.32$) and then *Smaller* ($M = 4.40, SD = 1.61$).

4.2.2 *I am satisfied with my performance in the task.*

SHAPE-CONDITION Regarding subjective performance, comparisons showed significantly ($p < .001$) higher ratings of *Cube* ($M = 6.43, SD = 0.67$) compared to *Sphere* ($M = 6.08, SD = 0.83$) or *Pyramid* ($M = 5.94, SD = 0.88$), but no significant difference between *Sphere* and *Pyramid*.

SIZE-CONDITION For SIZE, post-hoc tests showed significant ($p < .001$) difference between *Matching* ($M = 6.39, SD = 0.69$) and *Smaller* ($M = 6.03, SD = 0.83$), as well as *Bigger* ($M = 6.27, SD = 0.73$) and *Smaller*. Additionally. it revealed a significant ($p < .05$) difference between *Matching* and *Bigger*.

4.2.3 *It was easy for me to achieve my level of performance.*

SHAPE-CONDITION Post-hoc comparisons showed significantly ($p < .001$) higher ratings of *Cube* ($M = 6.45, SD = 0.71$) compared to *Sphere* ($M = 5.81, SD = 1.26$) or *Pyramid* ($M = 5.66, SD = 1.24$), but no significant difference between *Sphere* and *Pyramid*.

SIZE-CONDITION Similarly, we see significant ($p < .001$) differences between *Matching* ($M = 6.43, SD = 0.76$) and *Smaller* ($M = 5.92, SD = 1.02$), as well as *Bigger* ($M = 6.26, SD = 0.89$) and *Smaller*. Additionally. we found a significant ($p < .01$) difference between *Matching* and *Bigger*.

4.2.4 *I think the other person performed their task well.*

SHAPE-CONDITION We found significantly ($p < .001$) higher performance ratings for *Cube* ($M = 6.54, SD = 0.0.58$) compared to *Sphere* ($M = 6.29, SD = 0.70$) or *Pyramid* ($M = 6.28, SD = 0.71$). The ratings for *Sphere* and *Pyramid* are not significantly different.

SIZE-CONDITION For SIZE, we did not compute post-hoc comparisons as we found no significant main effect in LRTs.

4.2.5 *The visualization of the object matched the physical object well.*

SHAPE-CONDITION For subjective ratings of visuo-haptic congruence, post-hoc tests show significantly ($p < .001$) higher ratings for *Cube* ($M = 6.04, SD = 1.07$) than *Sphere* ($M = 2.84, SD = 1.80$) or *Pyramid* ($M = 1.65, SD = 1.65$) but no significant difference between *Sphere* and *Pyramid*.

SIZE-CONDITION Tests reveal significant ($p < .001$) differences among all levels of SIZE, which *Cube* subjectively matching the best ($M = 5.93, SD = 1.21$), followed by the *Bigger* ($M = 5.03, SD = 1.58$) and lastly *Smaller* ($M = 4.11, SD = 1.66$) visualizations.

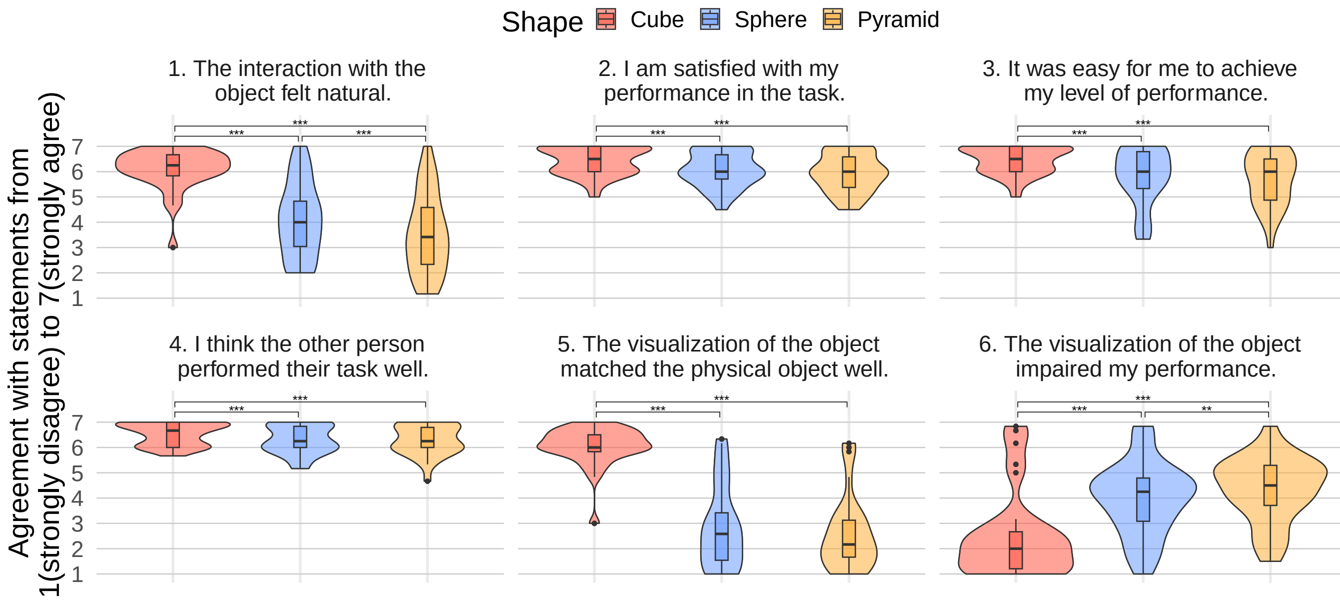

Fig. 3: Agreement ratings for our questionnaire statements in the SHAPE-CONDITION. Box and violin plots depict the distribution of ratings for levels of SHAPE averaged over all levels of OTHERSSHAPE and ROLE. Brackets and asterisks mark significant pairwise differences between groups found in post-hoc comparisons ($* = p < .05, ** = p < .01, *** = p < .001$).

4.2.6 *The visualization of the object impaired my performance.*

SHAPE-CONDITION We found significantly ($p < .001$) lower ratings for *Cube* ($M = 2.54, SD = 1.92$) than *Sphere* ($M = 3.97, SD = 1.63$) and *Pyramid* ($M = 4.35, SD = 1.49$) and a significant ($p < .01$) difference between *Sphere* and *Pyramid*.

SIZE-CONDITION Post-hoc comparisons again showed significant ($p < .001$) differences among all levels of SIZE, which *Cube* causing the least subjective impairment on performance ($M = 2.61, SD = 1.88$), followed by the *Bigger* ($M = 3.06, SD = 1.77$) and lastly *Smaller* ($M = 3.76, SD = 1.70$) level.

4.3 Qualitative Findings

In this section, we present the qualitative findings derived from the semi-structured interviews we conducted with participants after the experiment. We structure them based on the discovered overarching themes of the shift in the participants' reliance on different sensory channels (see section 4.3.1), their resulting strategy changes (4.3.2), and their perceived adaption to the visuo-haptic and interpersonal incongruencies (4.3.3).

4.3.1 Shifting Reliance on Sensory Channels

A common theme among interviewed participants was the shifting reliance on visual and haptic senses for the interaction. Participants were more dependent on their sense of touch, especially during the handover: *"I touched the object a couple of seconds, and then I took it from him so I know that I'm actually getting the object"* (P14a). Visual cues were mainly employed before touching to locate the object and prepare the strategy for the grasping action: *"I was pretty much relying on what I'm seeing [to determine] where to move or how to or where to reach or approach an object. But while I'm actually handling it, I was more trusting my sense of touch"* (P06a).

However, this reliance on visual cues before touch caused some issues when they were not aligning: *"It was larger, so, I mean, my instinct was to hold it more widely"* (P03a). These challenges ultimately caused participants to lower their trust and reliance on vision: *"I didn't trust what I was seeing. I was just like feeling like a blind person"* (P03b).

4.3.2 Strategies for Attention & Sensorimotor Behavior

Participants developed explicit strategies to handle the handover task. Regarding their actions, participants noted they generally defaulted to handing the object over while grasping the sides and receiving it with their hands underneath. They felt this decreased the likelihood of dropping the object: *"To hand over, it was better to use the sides and to receive the object, I'll just go underneath it, so I just cover the whole area, I won't drop it"* (P06b). Additionally, it could handle the visuo-haptic discrepancies well, for instance, with the *Smaller* visualization: *"Yeah, but with the small object, it was easier to grab it from the bottom"* (P10a). Alternative strategies were rarely employed, though some participants chose the inverse strategy: *"I tried to touch the bottom, so it was more easy for the other person to grab the hands from both sides"* (P13a). After strategies were formed, they remained mostly unchanged as participants relied on world knowledge: *"I would learn what the actual size of the box was, and whenever I saw that the visual or the virtual box was bigger, I would have already known that I trained my hands [...] to grasp a smaller object"* (P11b). However, the selection of which strategy to use was occasionally adjusted based on the visualization: *"From the side, if it's smaller and if it's larger then from the bottom"* (P03b).

In the handover task, participants differed in their attentional focus; some concentrated primarily on the virtual object, while others relied more on the representations of the other's hands: *"I will also look at what shape she got, so I already knew, for example, she could make a larger thing that I have to hold it a little closer"* (P03a). *"Not the virtual object. It was more the hands of the other person or my hands"* (P10a). As a rationale for prioritizing the object over the hands, participants cited inaccuracies in hand tracking reducing their trust in hand visualizations: *"I tried to look at her hands, but I didn't know if I could trust them because sometimes they were flying around"* (P03b). Consequently, alternative approaches to identifying the hand positions without relying on vision were developed: *"I was trying to sometimes feel my partner's hand because the objects were different than the box"* (P07a). The distribution of participants' attention was also influenced by the manipulations: *"For the cubes, especially for the big ones, I think it was easier to focus on the virtual object [...], but with the triangles [Pyramid], there always I focus on the hands"* (P10a).

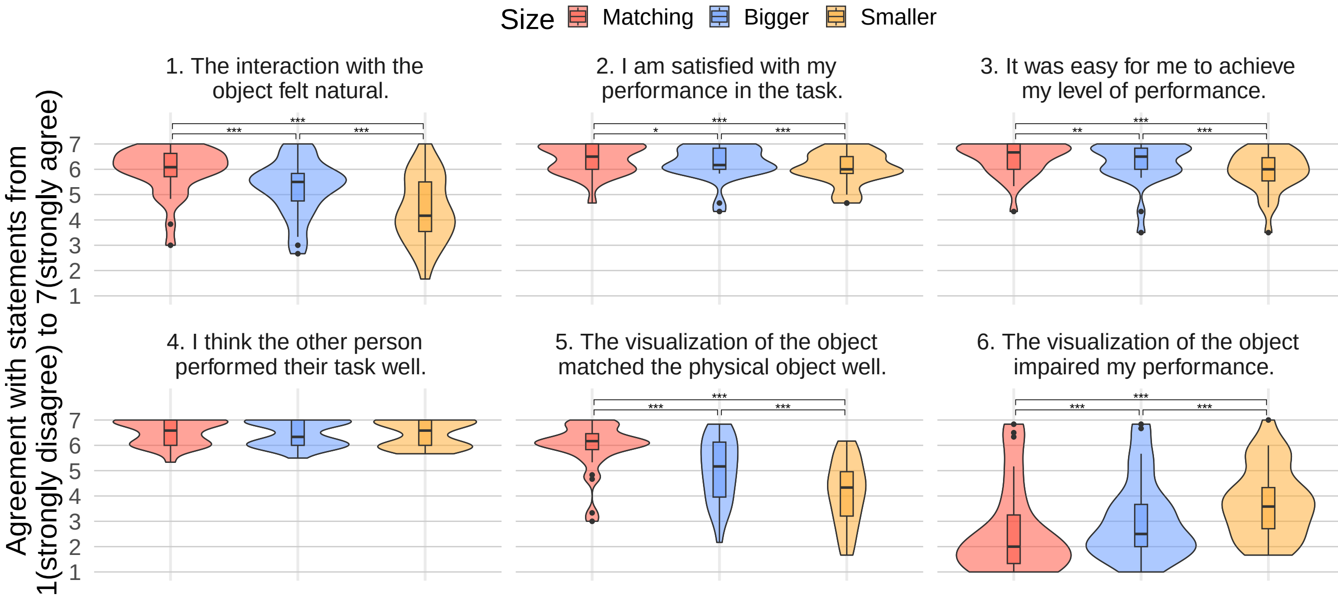

Fig. 4: Agreement ratings for our questionnaire statements in the SIZE-CONDITION. Box and violin plots depict the distribution of ratings for levels of SIZE averaged over all levels of OTHERSSIZE and ROLE. Brackets and asterisks mark significant pairwise differences between groups found in post-hoc comparisons ($* = p < .05, ** = p < .01, *** = p < .001$).

4.3.3 Adapting to Incongruence

While participants did not find overcoming the mismatches overly difficult, they noted that maintaining their performance required conscious mental effort: *"I always had to remind myself that it's not a ball"* (P15b). *"I had to, you know, switch on my mind every time"* (P11a). *"We had to stay alert because we did not know what shape we were going to handle"* (P02b). Hand tracking – even with employed hand redirection – helped participants link the virtual to the physical object through proprioceptive, haptic, and visual cues: *"You could always see your hands where it was. So that helped gauge, see how the structure was in respect to what we were seeing and what the real thing was"* (P12a).

Participants felt they adapted to the interaction with the visual-haptic discrepancies, making it easier and more natural over time: *"We just got better, and somehow, by the end, it also felt more natural than at the beginning"* (P01b). *"Over time I just got used to the point that maybe the object might not be the same shape as I visualized"* (P06b). However, participants noted this adaption was harder for some visualizations, especially the *Pyramid*: *"Through the whole experiment I had problems with the pyramid"* (P15b). *"The pyramid [...] was the smallest object and that might have been a bit more difficult [...] to adapt to"* (P11b).

Further, participants perceived the handover to be more challenging and unsafe than the pick-up from the stationary platform: *"Picking up [...] was very easy, but the handover, even if you've done it so many times, it was always tricky"* (P08a). *"I think grabbing it from the starting point, [...] I know it's in a safe position, I cannot drop it. But getting it from [the other participant], it was sometimes a little bit scary"* (P09a).

Participants generally did not seem to notice the discrepancies in visualizations between them and the opposing participant. When informed, the majority reacted surprised, while some mentioned some suspicions. However, participants believed that these changes did not affect their strategy: *"If I see a cube and he sees a pyramid, he would still try to grab it from the bottom"* (P12a).

5 DISCUSSION

Our results show that visual shape and size manipulations significantly impacted users' performance, subjective experience, and strategies. In the following section, we discuss these findings, structured around our research questions. We first examine the effects of visuo-haptic (see section 5.1) and interpersonal incongruence (5.2) on performance and user experience in a collaborative handover task (RQ1), followed by an analysis of adaptation strategies (5.3, RQ2). As this is the first study exploring HIs in a collaborative XR setting, we also derive practical recommendations and guidelines for integrating these illusions into such contexts (5.4). Lastly, we discuss the boundaries of our investigation and propose future research directions that may support establishing HIs as powerful tools to enrich haptic experiences in future collaborative XR (5.5).

5.1 Visuo-haptic discrepancies negatively impact users' performance and experience

Incongruent visuo-haptic representations of shape and size significantly impacted user performance and subjective experience in this collaborative task. This finding is in line with the results of single-user studies [31, 46]. Discrepant visualizations of local surface orientation (*Pyramid*), local curvature (*Sphere*), and volume (*Bigger*/*Smaller*) led to longer completion times and lower subjective ratings, such as the naturalness of the interaction and participants' self-assessments of their own or the other's performance. Participants reported exerting conscious mental effort to adapt but felt they eventually adjusted, both cognitively — finding the task more natural over time — and behaviorally — developing sensorimotor strategies to compensate for unreliable visual cues. The physical prop was never dropped during the study, showing that difficulties inherent to incongruent presentations can be successfully overcome. However, despite learning effects, which participants reported and we confirmed in TCT, handovers with incongruent stimuli still exhibited significantly increased completion times, suggesting participants had to slow down to remain consistent.

Participants consistently rated the *Pyramid* and *Smaller* visualizations as the most demanding in their respective conditions. The lower ratings and worse performance of *Pyramid* compared to *Sphere* suggest that mismatches in local surface orientation were more challenging to adapt to than local curvature. However, absolute comparisons of the dimensions of local orientation and local curvature of two primitives are difficult concerning their objective and subjective magnitude of discrepancies (e.g, *Is a Cube more similar to a Sphere or a Pyramid?*; refer to [46] for findings on the subjective similarity of discrete objects). Nevertheless, visuo-haptic discrepancies in local orientation have been shown to be detected earlier (i.e., lower just-noticeable-difference) by participants than curvature mismatches [48], and the *Pyramid* shape was generally perceived as the least matching to the physical shape by participants. This heightened sensitivity to discrepancies likely contributed to the reduced performance and subjective ratings for *Pyramid*. Additionally, the *Pyramid* was perceived as the smallest shape, aligning with its lower overall volume despite a constant base width. This reduction in volume may have further impacted performance and experience, analogous to the *Smaller* level in the SIZE-CONDITION.

Here, the reduction in size was also noticed more and rated as less matching the actual size than the *Bigger* condition, which similarly justifies its worse objective and subjective performance. In AR contexts, prior research has found size manipulations to generally be less disruptive to user experience than shape changes [31]. While both manipulations had significant main effects, this trend is reflected in our results: the average differences between matching and manipulated visualizations were generally less pronounced for size changes—particularly for *Bigger* visualizations (see Figure 3 and Figure 4, or subsection 4.2 for exact group means).

5.2 Effects of interpersonal mismatches can outweigh visuo-haptic incongruence in asymmetric tasks

In our study, we deliberately manipulated object visualizations at an individual level, introducing two potential incongruencies: (1) between physical shape and individual visualization (see subsection 5.1) and (2) between both participants' visualizations. Subjective ratings and qualitative insights indicate that visuo-haptic incongruence had the greatest impact, while interpersonal incongruence was less noticed. Completion times support this, with significant effects observed only when the *Receiver* experienced visuo-haptic incongruence for shape manipulations. However, for size manipulations, interpersonal mismatches significantly affected task completion. Unsurprisingly, *Matching* sizes between participants performed best. However, while increasing the *Giver*'s size from *Matching* to *Bigger* performed nearly as well as the fully *Matching* condition, changing the *Receiver*'s visualization to *Bigger* led to the worst performance – even surpassing visuo-haptic mismatches for both (i.e., *Bigger* → *Bigger* or *Smaller* → *Smaller*). This suggests that interpersonal congruence can, in some cases, outweigh visuo-haptic congruence, particularly for the *Receiver*, and that the individual role of the user plays a key part. This was reinforced by participants' interviews, which highlighted the increased difficulty of receiving due to compounded discrepancies and the dynamic, less predictable movement of the *Giver*.

5.3 Users consciously adapt by shifting reliance to touch but cannot fully compensate for vision

Participants adapted to visuo-haptic mismatches by shifting reliance from vision to haptic and proprioceptive feedback. This adaptation, reported by participants and evident in sensorimotor strategies, prioritized a stable grasp of the physical cube, largely independent of visual input. This aligns with the maximum likelihood model of visuo-haptic integration, where sensory weighting is based on the reciprocal variance of senses [18]. As visual reliability decreased in our experiment, perception increasingly depended on haptic information over vision. This likely originated from the fact that the reliability of sensory information in our study was shaped by prior world knowledge. Participants expected visual inconsistencies while anticipating a static physical presentation.

Participants felt their adaptation improved object handling over time, and we observed performance changes across trials, likely reflecting general learning effects. To account for this in our analysis, we randomized condition orders between sessions and included the trial numbers in our mixed-effects models. Even with these controls, incongruent visuals still significantly affected performance, suggesting that the effects observed are robust and would likely be stronger in the absence of adaptation. This indicates that vision remains crucial for grasping and cannot be entirely substituted by other sensory modalities. Studies on visuo-haptic grasping emphasize vision's critical role in guiding reach-to-grasp actions, providing reliable location cues (which remained stable in our study) and size/shape information (which we manipulated) [11, 44]. While learning effects are expected, there is a distinction between learning the task itself and learning how to cope with sensory incongruence. Prior work shows that people can adapt to constant visuo-haptic discrepancies in local orientations [54] or sizes [53] through fixed sensory-to-motor transformations, enabling compensation for unreliable vision. However, in our study, object visualizations changed after each handover, preventing adaptation to a static discrepancy. As a result, participants had to consciously account for visual unreliability in every grasp, explaining its negative impact on performance and strategy despite perceived adaptation.

Regarding potential inter- and intrapersonal factors, prior single-user investigations have demonstrated individual variability in visuo-haptic tasks. For instance, age [38] and finger size [41] affect haptic acuity, and sensitivity to sensory incongruence varies between individuals [22, 32] or when distractions are added [58]. We aimed to mitigate the influence of these factors by using large, clearly noticeable stimuli and discrepancies for our investigation. However, regarding contextual factors, we found that participants' difficulty in adapting to the HI was influenced by the user's individual task (*Giver* or *Receiver*) in the interaction, which indicates that adaptation to mismatches is task- or role-dependent. This highlights the importance of designing HIs that account for individual contexts, especially in complex collaborative tasks, for instance, by personal calibration approaches [21, 55].

5.4 Guidelines for the integration of Haptic Illusions into Collaborative XR

In this work, we explored the challenges of integrating HIs into handover tasks to enhance future haptic experiences in collaborative XR, which still rely solely on passive props. Based on our quantitative and qualitative findings, we provide guidelines for researchers and designers to adapt HIs from single-user scenarios to these novel multi-user contexts.

5.4.1 Design physical props smaller and augment their size virtually.

Our results show that visuo-haptic mismatches are more disruptive when the virtual object appears smaller than the physical prop, particularly for certain shapes like the *Pyramid*. To minimize perceptual inconsistencies and allow for dynamic size or shape variations, we recommend constructing smaller physical objects and using HIs to achieve the desired larger virtual appearance.

5.4.2 Set more conservative boundaries for visuo-haptic discrepancies.

While prior work in single-user contexts showed that a small set of physical primitives can support a wide range of virtual shapes and sizes [31, 46, 47], our findings suggest that this flexibility does not fully translate to collaborative scenarios. Incongruencies that may be sufficient for single-user interactions may become disruptive when multiple users interact with the same prop, as evidenced by reduced performance and subjective ratings in our study. Consequently, we recommend applying more conservative limits to visuo-haptic manipulations when transferring findings from single-user investigations. This may require a broader set of physical primitives to maintain immersion and performance.

5.4.3 Minimize mismatches for the more demanding role or synchronize mismatches across users.

Using HIs to extend the capabilities of physical props inherently requires introducing controlled mismatches. We found that users in more demanding roles – such as the *Receiver* in handovers – were more affected by these mismatches. However, we found that these mismatches are less disruptive when they are applied consistently across both users. Therefore, we recommend reducing mismatches for the more sensitive role whenever possible or keeping them consistent across both users to preserve interaction quality.

5.4.4 Support adaptation through multimodal cues and prior knowledge

Our findings reveal strong learning effects during exposure to visuo-haptic mismatches. Participants used sensorimotor strategies and multimodal cues to adapt, for instance, watching or touching their partner's hands rather than the object, or comparing visual and proprioceptive feedback of their own hands. They also leveraged their awareness that the physical prop remained unchanged to interpret the visual manipulations more effectively. Providing multimodal cues, integrating users' prior world knowledge, and allowing time for strategy formation can significantly enhance users' adaptation, performance, and overall experience.

5.5 Limitations & Future Work

Our study takes an initial step toward integrating HIs into collaborative XR. However, adapting these phenomena from single-user studies to complex multi-user settings introduces practical constraints and novel aspects that a single study cannot fully explore.

First, we deliberately focused our investigation on large, distinctly noticeable manipulations in visual shape and size to examine the extreme cases of mismatch. HI manipulations near or within their respective detection thresholds are likely to influence the measured metrics to a lesser extent. The effect of these elicitations and the transferability of established detection thresholds to collaborative XR contexts require further investigation.

Further, we quantified users' performance based on completion times, which might not always be the sole critical metric depending on the XR scenario. Professional training might favor accuracy and safety over speed. However, to measure accuracy, we would first require precise knowledge of optimal task completion, which needs to be determined based on the individual setting requirements. To determine safety and consistency, failure rates (e.g., how often users drop or misplace the object) could be investigated, which would, however, require much more demanding task procedures to induce frequent errors. Instead, we opted for a broader metric and complemented this with qualitative insights. Future work might look into alternative measurements to acquire more target-specific insights.

Additionally, our approach was constrained by current limitations in hand tracking, which participants frequently found unreliable. We employed an established optical method shown to be accurate [49], including through acrylic glass [50]. Nevertheless, these systems still require direct visibility of the hands and are prone to occlusion errors. While all conditions were affected, including congruent ones, such unreliability may impact collaboration strategies, as they introduce additional incongruence to visuo-proprioceptive interactions, which warrant their own investigation.

Lastly, our study focused specifically on one core aspect of haptic feedback in collaborative XR: the handover of a physical object. We selected this task because it represents a fundamental interaction requiring synchronous coordination with a shared prop. However, many other scenarios could benefit from passive props and HIs, such as joint object carrying, physical contact in competitive games [23], collaborative assembly [1], or medical training [45]. These settings may demand more than shape or size manipulations, for instance, HIs that simulate stiffness [56] and weight [43] to convey material properties or temperature [24] to produce safe and scalable scenarios. Especially in training scenarios where accuracy is critical, both the benefits and risks of applying HIs must be carefully evaluated. As our findings suggest that collaborative use of HIs can differ significantly from single-user results, we advocate for future research to extend established HIs to more ecologically valid contexts.

6 Conclusion

Realistic haptic feedback is crucial for physical collaboration but remains challenging in multi-user XR, where systems typically rely on static passive props. HIs have shown promise in single-user contexts but are largely unexplored in collaborative scenarios. To investigate their applicability to these contexts, we conducted a user study examining the effects of shape and size illusions on performance, experience, and behavior during a VR handover task.

We found that visual-haptic mismatches disrupted collaboration, leading to reduced performance and user experience. While users adapted over time using multisensory cues and sensorimotor strategies, visual inconsistencies could not be fully compensated. Further, the influence on performance was affected by users' roles in the interactions and the synchrony of individual visualizations. These insights highlight the need for more careful use of HIs in collaborative XR – by managing mismatches more conservatively, supporting adaptation through cues and training, and accounting for role-based differences. With these findings and recommendations, we lay the groundwork for the integration of HIs into multi-user contexts, supporting the development of richer and more adaptable haptic experiences for future XR collaboration.

7 Open Science

We provide access to our collected datasets, Unity project, code-set for the interviews, and data analysis scripts at this link: https://osf.io/ugnf4/.

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