MoveTogether: Exploring Physical Co-op Gameplay in Mixed-Reality

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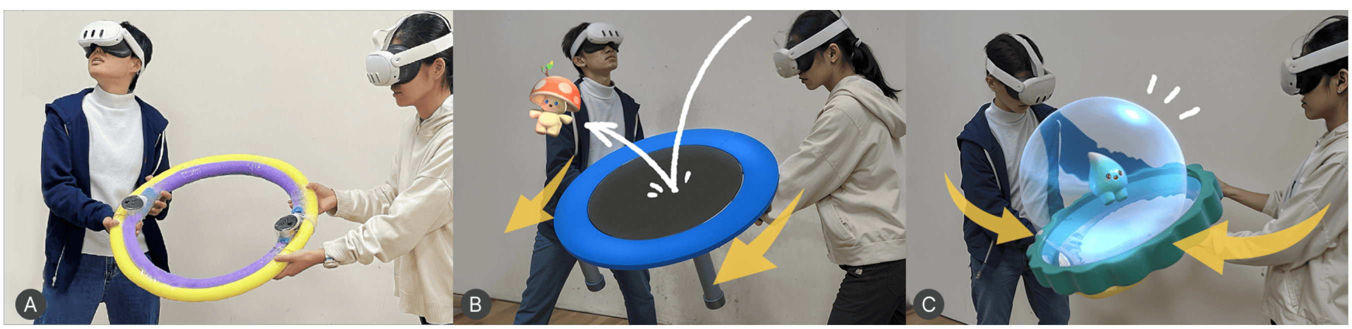

Figure 1: MoveTogether introduces PHYSICAL CO-OP, where two co-located players jointly operate a single shared prop, augmenting conventional verbal and visual communication with a shared physical communication channel. Players: (a) co-manipulate a physical prop which transforms into different virtual shared objects virtually with different interactions: (b) moving a virtual trampoline together to catch and bounce game characters, and (c) squeezing a nozzle together to create a floating bubble.

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Abstract

Current co-op games keep collaboration virtual even when players are physically co-located in the same room, limiting embodied coordination in the shared space. We introduce MoveTogether, a novel physical co-op gameplay in which two players jointly operate a single, tracked prop, adding a shared physical communication channel on top of visual and audio cues. To explore the design space in mixed reality, we conducted a workshop with 10 professional designers, generating a physical co-op design space that encompasses prop and interaction design patterns, and how they relate to affordance and cooperative experience. In a within-subjects study of virtual vs.

physical co-op experiences (n=16), we observed finer-grained task coordination, fewer collisions, and more strategy-focused communication. Players reported higher collaboration, sense of achievement, enjoyment, and overall preference for physical co-op. This work opens a new design space for co-located play and offers guidance for designing embodied co-op experiences.

CCS Concepts

• **Human-centered computing → Interaction design**; **Mixed reality**.

Keywords

Mixed Reality, Shared Haptic Controller, Co-Located Collaboration, Tangible Interaction

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1 INTRODUCTION

Co-op games bring people together, with players aligning on goals, communicating, coordinating, and sharing both challenges and successes [25]. They promote meaningful social [37], cognitive [4], and emotional growth [18], while enhancing social closeness [21], teamwork [57], and trust [33, 53]. Yet even when players are in the same room, current co-op games (e.g., *It Takes Two*, *Overcooked*, and *Moving Out*) keep collaboration virtual with players using separate controllers to control separate avatars, limiting embodied teamwork in the shared physical space where HCI has long shown that tangible and bodily interaction can scaffold coordination and mutual awareness [42, 46, 60].

In this paper, we introduce MoveTogether, a PHYSICAL CO-OP mechanic in which two players jointly operate a single tracked prop, adding a shared physical communication channel on top of visual and audio cues. By embedding collaboration in the physical world, rich nonverbal cues, haptic coupling, and mutual constraint become available when people act on the same physical object. Everyday activities such as jointly carrying an object illustrate how shared physical effort naturally drives teamwork and communication. While prior work has explored shared haptics for remote collaboration [13, 16] and co-located MR games with separate controls [44, 70], the design space of jointly-operated props and interactions for co-located gameplay remains underexplored.

To explore the design space of PHYSICAL CO-OP in mixed reality (MR), we conducted a workshop with 10 professional designers and summarized key prop design dimensions and interaction design primitives, identifying how prop properties, such as geometry, scale, and rigidity, shape affordance—the perceived action possibilities provided by the object's physical form [42]—and cooperative dynamics. Guided by these insights, we implemented a MoveTogether MR game based on a ring-shaped prop. To understand the experience of VIRTUAL CO-OP VS PHYSICAL CO-OP, we conducted a within-subjects study (n=16). PHYSICAL CO-OP produced finer-grained, moment-to-moment coordination, fewer collisions and near-misses, and more strategy-focused communication. Participants rated PHYSICAL CO-OP higher on collaboration, sense of achievement, engagement, enjoyment, and overall preference.

To contextualize our work, we map representative co-op games onto a two-dimensional space defined by whether two players jointly operate a *shared physical controller* to jointly control a *shared virtual object*, as shown in Figure 2. We term VIRTUAL CO-OP to represent collaboration through separate physical controllers, whereas PHYSICAL CO-OP is collaboration through joint manipulation of a shared physical object. This distinction situates our contribution and highlights the underexplored potential of embodied teamwork. This mapping focuses on co-op, whereas the 'Bodily Interplay' framework by Mueller et al. [52] categorized *non-coop* multi-player games by shared space, body, and object.

The majority of current co-op games have each player operating an independent controller-avatar pair to coordinate. Examples include *Overcooked* [29], *Portal 2* [72], and team battle games, which are in the Figure 2.b: SEPARATE PHYSICAL CONTROLLERS x SEPARATE VIRTUAL OBJECTS quadrant. A smaller set of co-op games has partners using separate input devices to operate a single virtual object. Examples include *Moving Out* [69], in which two players jointly carry large furniture virtually, and *Kinect Adventures* [31], in which two players operate the same river raft. These games are in Figure 2.a: SEPARATE PHYSICAL CONTROLLERS × SHARED VIRTUAL OBJECT quadrant. In contrast, the SHARED PHYSICAL CONTROLLER half of the design space remains underexplored.

Our key contributions are: 1) introducing the concept of PHYSICAL CO-OP, a gameplay mechanic that augments conventional verbal and visual communication with a shared physical communication channel via a jointly manipulated prop; 2) a design-space exploration grounded in a designer workshop that surfaces prop-level design dimensions and interaction primitives, and identifies embodiment, interaction primitive, and coordination mode as axes for structuring co-located cooperation; 3) an empirical comparison showing that PHYSICAL CO-OP supported tighter coordination and safety, with implications for co-located MR game design; and 4) open-sourcing of our MR game[1] for others to experience and further explore PHYSICAL CO-OP interactions.

2 RELATED WORK

Our work is situated at the intersection of co-op games and embodied tangible interaction. The concept of "shared control" spans from turn-based control of a remote robot to distributed inputs for a single avatar. We review prior work by the medium of collaboration.

2.1 Virtual Co-op Games

Virtual co-op games are widely explored in digital contexts, where collaboration is mediated through avatars and individual controllers across console, PC, VR, and MR platforms. Commercial titles such as *It Takes Two* [41], *Overcooked* [29], and *Moving Out* [69] show how distinct inputs support teamwork through timing, strategy, and complementary skills. In VR/MR, research emphasizes symbolic actions rather than shared embodiment: cooperative puzzle-solving

[1] https://github.com/ntu-hci-lab/MoveTogether

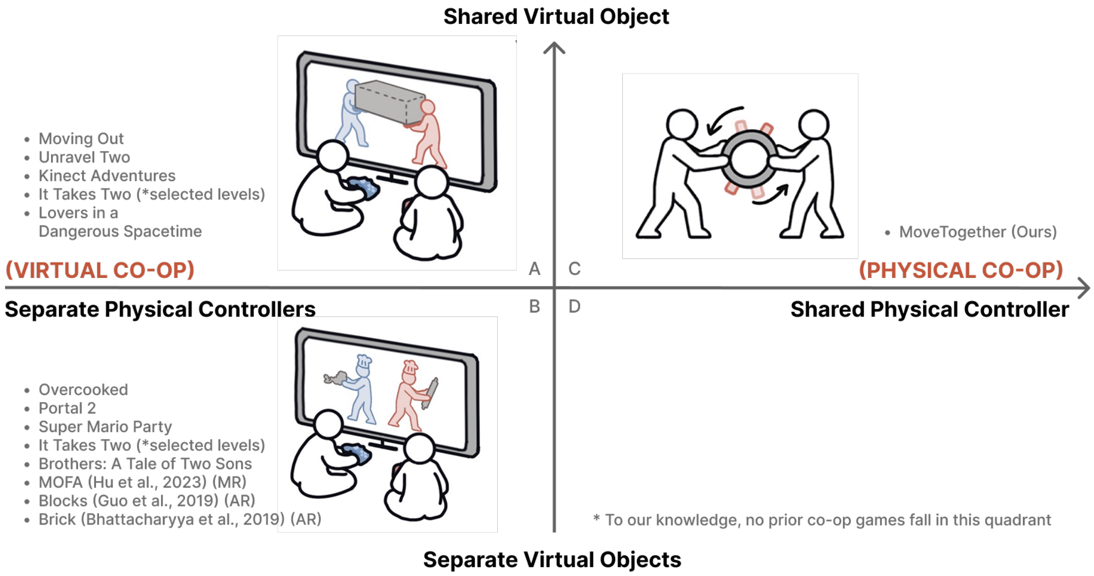

Figure 2: Representative co-op games positioned by whether players collaborate through *shared vs. separate physical controllers* to jointly control *shared vs. separate virtual objects*. Most existing co-op games are in the VIRTUAL CO-OP half of the space, while the *Physical Co-op* half remains underexplored.

highlights teamwork [14], facial-expression sharing augments social presence [38, 39], eating actions enhance trust [1], and comparing cooperative vs. competitive MR modes shows collaboration improves connectivity and immersion [51].

Beyond separate avatars, studies explore shared control of a single entity. CoplayingVR [82] and PairPlayVR [83] analyze how divided inputs affect fairness and agency, while cross-platform mechanisms [47] examine synchronization across devices. Hybrid projects combine tangible and virtual play: Lab2 merges board-game mazes with VR navigation for collaborative learning [5], and Art of Defense uses handheld AR for embodied cooperation [45]. This domain of Collaborative Augmented Reality (CSCAW) was pioneered by foundational systems enabling co-located interaction [7]. In MR, Brick introduced a co-located AR game with a synchronous multiplayer model [6], Blocks supported persistent collaborative construction [34], and MOFA applied asymmetric roles and perspectives across prototypes [44].

Overall, the majority of these approaches focus on digital-only collaboration, where coordination is symbolic—button presses, avatar actions, or mediated cues. What remains underexplored are embodied teamwork forms leveraging nonverbal communication, shared constraints, and co-manipulation of objects, central to richer and more natural cooperation.

2.2 Physical Co-op Games

Physical co-op activities such as three-legged races, tug-of-war, canoeing, and group jump rope have long been an important part of human play [63, 76, 80]. These activities illustrate how shared constraints demand synchronized movement, bodily awareness, and nonverbal communication [66, 67]. Game studies frame this as co-located physical social play, where coordination and joint effort foster trust, teamwork, and enjoyment [65]. Yet digital games mostly mediate collaboration through avatars and separate controllers, limiting embodied cooperation [26, 78].

The academic exploration of such digitally-augmented play was shaped by early Tangible AR. Billinghurst et al. provided both the conceptual foundation and toolkits for using physical objects as intuitive controllers [8], linking TUI principles [46] to collaborative interaction. Building on this, HCI researchers developed co-located haptic and tangible systems to enrich shared play. Mutual Human Actuation [17] linked players with a prop for force-feedback in synchronized tasks. Give Me a Hand [10] enabled bidirectional embodied interaction with shared real–virtual objects. Rope Revolution [79] and RopePlus [80] turned ropes into tangible interfaces supporting collaborative gestures, haptics, and remote coupling. Extending this, Hashiura et al. [40] showed that shared haptic feedback across controllers enhances collaboration when two players manipulate one virtual object. Collectively, these works demonstrate how tangible interfaces scaffold awareness and coordination.

While Tangible AR emphasizes co-located interaction, a parallel TUI challenge has been remote sharing. Early systems like inTouch [12] embodied this idea, creating a "tangible telephone" where partners felt each other's manipulations. The notion of Synchronized Distributed Physical Objects [13] advanced remote collaboration. More recently, I'm in Control! [3] examined ownership transfer of haptic props in distributed VR, revealing trade-offs between efficiency and communication.

The work above shows that co-located play and shared haptics, whether local or remote, foster coordination and connection. Yet most work either focuses on physical games without digital augmentation or on haptic systems for telepresence and training. While early exploration of co-located MR shared-prop like *Wandering Spirit* [74] demonstrated the potential of a single shared-prop implementation, it did not systematically examine the broader design space of physically coupled interaction. This work undertakes a broader and deeper systematic exploration. We first conceptualize co-op gameplay along two key dimensions, distinguishing virtual from physical co-op. We then populate this space through a formative design workshop and empirically validate these insights by comparing coordinated physical shared-prop play against a virtual baseline. Our findings reveal how shared physical constraints reshape the cooperation experience in mixed reality.

3 STUDY #1: DESIGN WORKSHOP

3.1 Study Design

To formatively explore the emerging design space of physical co-op interactions in MR, we adopted a co-design workshop approach centered on two-player interactions to study the dyad as the fundamental unit of collaboration, allowing us to isolate core coordination dynamics before introducing the complexities of larger group interactions.

To ensure a comprehensive exploration of the design space, we asked all teams to develop concepts for two distinct categories: handheld props (emphasizing manual control) and non-handheld props (emphasizing full-body coordination), and systematically explore how the scale of embodiment—from fine-grained manual control to full-body spatial coordination—shapes collaborative interaction. The study followed a research-through-design process involving rapid brainstorming, low-fidelity prototyping using craft materials, and embodied playtesting where participants enacted and evaluated each other's designs. This structure allowed us to capture not only the physical attributes of the artifacts but also the qualitative user experiences, such as affordance, haptic feedback, and coordination dynamics, that emerge during joint manipulation.

3.2 Participants

We recruited 10 participants (P1–P10) with professional design experience (M = 2.4 years, range = 1-5 years, SD = 1.79). Their backgrounds were in VR/MR design (n=5), game design (n=1), industrial design (n=2), and interaction design (n=2). The recruitment was carried out through online posts and personal referrals, and each participant received approximately USD $20. This study was reviewed and approved by our institution's ethics board, and all participants provided informed consent.

3.3 Study Procedure

Participants worked in pairs (two per team), forming a total of five teams. The workshop lasted approximately three hours and was structured into five phases:

Introduction (15 min). Facilitators outlined goals, reviewed examples of co-op play in digital and physical contexts, and set the design constraints: two players collaboratively controlling a single shared prop.

Paired Brainstorming (30 min). Each participant sketched 10 controller concepts—5 handheld and 5 non-handheld—individually (5 min). Teammates then discussed and refined ideas (5 min). Each group selected a handheld and a non-handheld idea to present in a 3-min pitch with a rationale (15 min).

Paired Prototyping (40 min). To balance creative breadth with exploratory depth within the workshop's time constraints, each team built low-fidelity prototypes of their two selected ideas using craft materials (one handheld, one non-handheld). After each build (15 min each), they spent 5 minutes brainstorming interaction ideas, aiming to generate up to five two-player co-manipulation interactions.

Idea Sharing (80 min). Teams demonstrated their prototypes to all participants in 2 rounds:

- *Handheld round (40 min):* Each team presented its handheld prop and the 5 associated interaction ideas (3 min presentation + 4 min live playtest by peers + 1 min note-taking). All teams rotated through, allowing every participant to experience each design.
- *Non-handheld round (40 min):* The same process was repeated for non-handheld props.

The presentation and playtest were round robin (Team 1 – Team 5). For the hands-on evaluation, due to time constraints, we randomly selected participants to playtest the props. We invited all participants to collaboratively discuss the prop until five interactions were defined. While order and exposure effects may influence participants' perceptions, this collaborative approach ensures that everyone can brainstorm together during playtesting, enabling a richer exploration of interaction and prop design possibilities. Facilitators documented the playtests using photography, video recording, and whiteboard notes.

Discussion and Ranking (40 min). To help participants compare alternatives and clarify their preferences across props and interactions, we asked them to evaluate each design using predefined criteria. Conducted after the hands-on trials, this exercise primarily functioned as a scaffold for reflection and conversation rather than as a central quantitative measure. To reduce bias, teams did not evaluate their own props or interactions. For each category (handheld and non-handheld), participants also ranked the four props created by other teams and, for each prop, the five associated interactions according to the criteria. After each ranking activity, facilitators conducted short interviews in which participants explained their choices, followed by a concluding group discussion to surface cross-cutting reflections.

3.3.1 Data Analysis. Our analysis focused on constructing a design space from the diverse workshop outcomes. To systematically interpret the props and interactions, we employed Reflexive Thematic Analysis (RTA) [11]. We adopted a constructivist analytic stance, acknowledging that the themes were generated through our interpretative engagement with the data, rather than existing as objective truths to be discovered. Our coding strategy was hybrid, combining deductive and inductive approaches [59] to address different analytical goals:

- ***Deductive Analysis*:** We applied deductive coding to analyze participants' verbal justifications for their comparisons. Codes were based on predefined criteria (Sec. 3.6). This allowed us to understand the specific reasoning behind participant preferences.
- ***Inductive Analysis*:** We applied inductive coding to the workshop outcomes (sketches, prototypes), interviews, and session recordings. This generated the structural patterns for prop attributes and recurring interaction primitives (Sec.

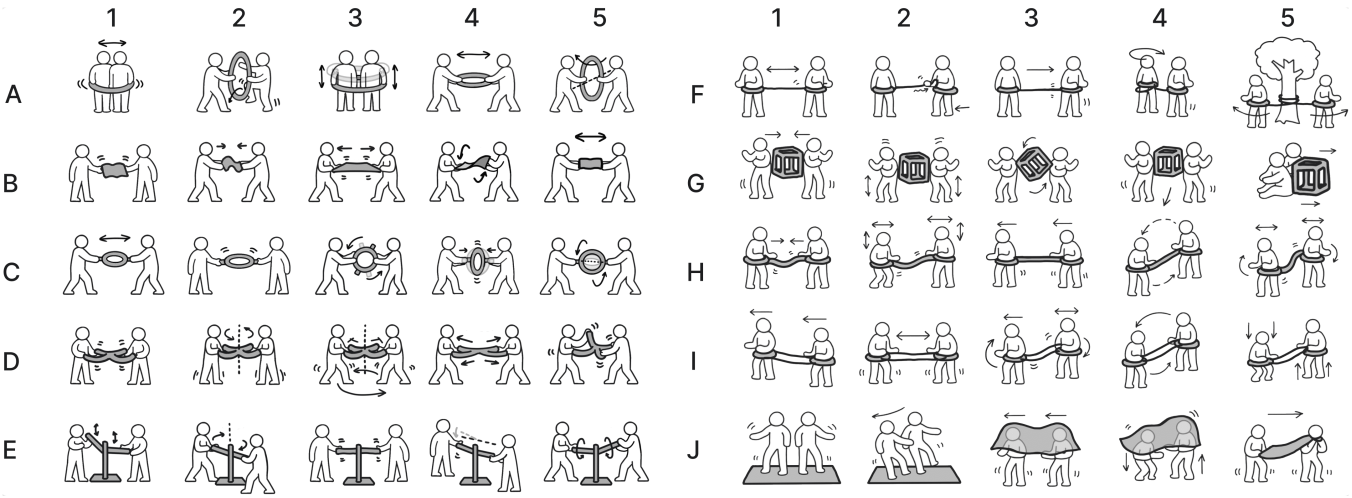

Figure 3: Ten participant-designed props (A–E handheld, F–J non-handheld), each illustrated with five two-player interaction patterns. Handheld props support fine-grained actions—including balancing, moving, squeezing, stretching, rotating, and flipping—while non-handheld props enable larger-scale, full-body interactions such as moving, rotating, stretching, lifting, and waving. The figure visualizes how different prop forms and grasping configurations afford distinct modes of coordinated movement.

3.5 and 3.6) and the latent themes regarding how these properties shape the interaction experience (Sec. 3.7).

The analysis was conducted by two researchers with distinct backgrounds: one with expertise in Architecture, Spatial Design, and Tangible Interaction, and the other in Game Design and Environment Design. This positionality allowed us to view the props through dual lenses.

Coding Process. We followed the six-phase approach outlined by Braun and Clarke [11]. We first familiarized ourselves with the dataset by transcribing video recordings of the presentations and playtests and integrating them with photos of the 10 prototypes. Two researchers then independently coded the transcripts and visual artifacts, identifying both semantic codes (e.g., explicit actions such as "squeezing" or "pulling") and latent codes (e.g., underlying dynamics such as "negotiation of control" or "haptic assurance"). When our interpretations diverged, we did not try to converge on a single "correct" code; instead, we discussed these differences to surface assumptions and refine themes. We iteratively collated these codes and, through critical collaborative reflection, rather than calculating inter-rater reliability, we organized them into descriptive dimensions regarding prop attributes and interaction primitives, and developed latent themes regarding how these physical properties shape prop affordances and the cooperative experience. To ensure analytic rigor, we documented analytic decisions through ongoing memoing and revisited candidate themes across both transcripts and visual artifacts, refining them through reflexive dialogue.

Complementary Quantitative Analysis. To summarize general preference trends within the ranking data, we combined descriptive and inferential analyses appropriate for within-subjects measures. For each prop and interaction set, we computed Mean Ranks (lower values indicating stronger preference). Given our small sample size ($N = 8$) and the ordinal nature of the data, we used non-parametric tests: separate Friedman tests for handheld and non-handheld props, and individual Friedman tests for interaction rankings within each prop. When omnibus tests were significant, we conducted Wilcoxon signed-rank post-hoc comparisons with Holm correction (all tests two-tailed, $\alpha = .05$). We report these statistics to provide descriptive context for the qualitative findings rather than as definitive outcome measures.

3.4 Results and Findings: Prop Design Dimensions

We analyzed ten props generated during the workshop—five handheld (Props A–E) and five non-handheld (Props F–J). Because these artifacts were created by participants with diverse design backgrounds, they varied widely in the body parts involved in manipulation, the inter-player distance they imposed, the geometric structures they adopted, and the types of force feedback they afforded. Across these participant-created props, four design dimensions emerged as particularly consistent in shaping how two players could coordinate their actions: grasping mode, size, geometry, and material.

Handheld vs. Non-Handheld.

(1) *Handheld props (A–E)* are manipulated directly with the hands, concentrating input through the wrists, arms, and fingers. This configuration supports fine-grained adjustments in angle, orientation, and distance. Because motion originates from relatively small joints with high degrees of freedom, these props offer precise directional control and localized force transmission.
(2) *Non-handheld props (F–J)* shift manipulation to larger body segments, including the waist (F, H, I), back (G), or the whole body (J). Movements therefore arise from torso rotation,

weight shifting, or full-body stepping rather than manual adjustments. As a result, motion signals tend to be broader in amplitude, less sensitive to small variations, and more strongly coupled to overall body positioning.

Size (Small; Medium; Large). The props span a size range of 30–150 cm, which directly determines the inter-player distance and the available motion envelope.

(1) *Small props (B, C, G; 30–60 cm)* place players in close proximity. For B and C, short mechanical linkages cause motion to propagate quickly between players. Prop G, although small, is operated back-to-back, producing a configuration where physical distance is minimal but face-to-face alignment is absent.
(2) *Medium props (A, D, F, H, I; 60–120 cm)* establish moderate spacing. Props A and D (90–100 cm) allow wide arm or torso movements; Props F, H, and I (around 70 cm) permit large lower-body gestures such as squatting, widening stance, or arm extension. These sizes support broad movement ranges but do not amplify small angular adjustments.
(3) *Large props (E, J; > 120 cm)* position players farther apart. Prop E (140 cm) is a grounded structure that constrains interaction to stationary rotations. Prop J (150 cm), made of fabric, does not restrict inter-player distance and accommodates substantial spatial flexibility, though at the expense of strong mechanical coupling.

Geometry (Radial; Quadrilateral; Bilateral). Geometric structure governs how forces are distributed, how grasping or attachment points are arranged, and how actions are partitioned between players.

(1) *Radial geometries (Props A, C)* Radial geometries offer continuous circular symmetry, supporting smooth reorientation and flexible grasp repositioning, making it easy for pairs to coordinate global direction shifts without encountering edges or discontinuities.
(2) *Quadrilateral geometries (Props D, G)* Quadrilateral geometries introduce four-sided or four-arm layouts that support mirrored roles at opposing edges. This structure affords stable two-player cooperation and can be readily scaled to four users. Prop D's cross-shaped form enables orthogonal force application, while Prop G's cubic frame distributes loads across multiple faces.
(3) *Bilateral geometries (Props B, E, F, H, I, J)* Bilateral geometries are defined by a clear left–right or front–back axis of symmetry. This symmetric layout naturally creates two equivalent sides. At the same time, the fixed bilateral form limits how forces can be redistributed across the object, which constrains movement range and provides fewer pathways for extending the interaction beyond two participants.

Material (Rigid; Semi-Rigid; Composite; Soft). Material properties influence deformability, force feedback, and the strength of mechanical coupling across the prop–body interface.

(1) *Rigid materials (Prop E; cardboard base and cardboard tube)* are used in the grounded platform and central support column of the prop. These rigid components exhibit minimal deformation, confining motion to fixed-axis, ground-contact patterns and preventing dynamic repositioning or flexible manipulation.
(2) *Semi-rigid materials (Props A–D, G–H; foam rods)* are used as the primary structural elements of these props, forming their rings, rods, or peripheral frames. Foam rods maintain shape without elasticity, providing consistent directional pressure and impact absorption.
(3) *Composite materials (Props F, I; foam rods with elastic or non-elastic cord)* combine a semi-rigid foam ring worn at the waist with a connecting cord that varies in elasticity. In Prop F, the elastic rope enables stretch-and-recoil behaviors; in Prop I, the non-elastic nylon cord preserves length while offering weaker immediate feedback.
(4) *Soft material (Prop J; fabric)* forms the entire sheet-like body of the prop, creating a fully deformable surface that can be pulled, folded, or stretched in any direction.

3.5 Results and Findings: Interaction Design Primitives

Despite the variety of prop forms, our analysis revealed a convergence on a core set of recurring interaction primitives. Across the 10 props and 50 interactions, participants repeatedly employed six key actions for handheld props and seven for non-handheld props, each shaping coordination in distinct ways. In the following section, we distinguish between geometric symmetry of the prop (e.g., bilateral or radial symmetry in its shape) and coordination patterns between players. For the latter, we describe players' movements as mirrored or synchronized when they perform similar actions at the same time, and complementary when they take on distinct but interdependent roles.

Figure 5 shows 5 handheld props and their 5 interactions. Each primitive shaped coordination in distinct ways:

(1) *Balance.* Stabilizing the prop through equal force along an axis or plane. This required tight *mirrored* coordination and was seen across multiple designs (e.g., B1, C1, C2, D1, E3, E4).
(2) *Move.* Translating the prop together in space (e.g., A1, A3, B5), or involving one player passing through or around the prop (e.g., A2). This enabled whole-body alignment, but often with looser coupling.
(3) *Squeeze.* Compressing or applying inward (e.g., B2, C4, E1) force to the prop. This enforced *mirrored* squeezing against resistance.
(4) *Stretch.* Pulling the prop apart (e.g., A4, B3, D4). This created *complementary* push–pull dynamics.
(5) *Rotate.* Turning the prop around a shared axis. This was the most frequent primitive, supported by the geometry of various props (e.g., A5, C3, D2, D3, E2, E5).
(6) *Flip.* Performing complex, non-mirrored actions such as twisting or inverting the prop (e.g., B4, C5, D5). This introduced playful unpredictability but risked misalignment.

Non-handheld props, due to their larger scale and different affordances, supported a distinct set of primitives:

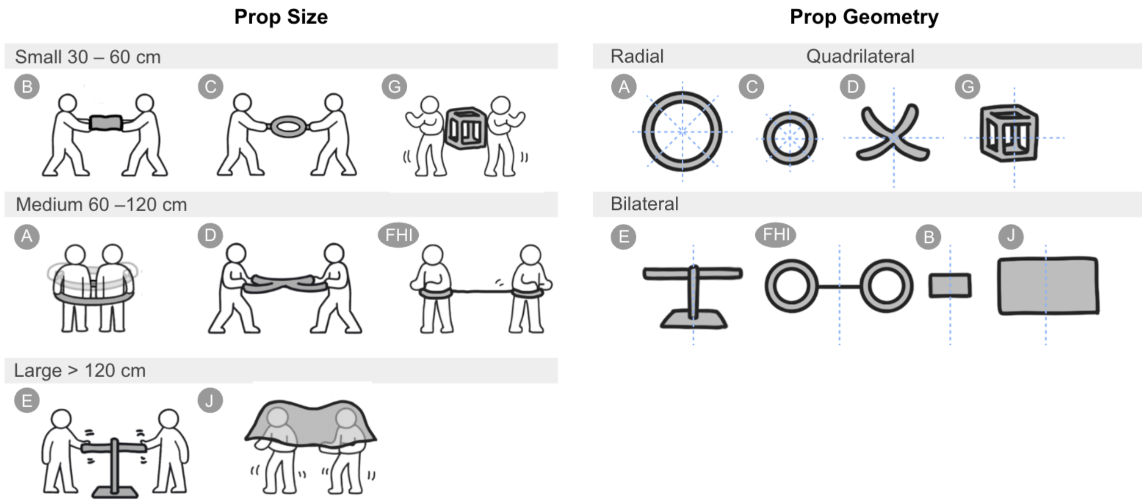

Figure 4: Prop size and geometry across the ten participant-generated designs. Left: Props categorized by size—small (30–60 cm), medium (60–120 cm), and large (>120 cm)—illustrating how different scales position players and shape available movement ranges. Right: Prop geometry classified into radial, quadrilateral, and bilateral forms, highlighting structural symmetries that afford distinct coordination patterns.

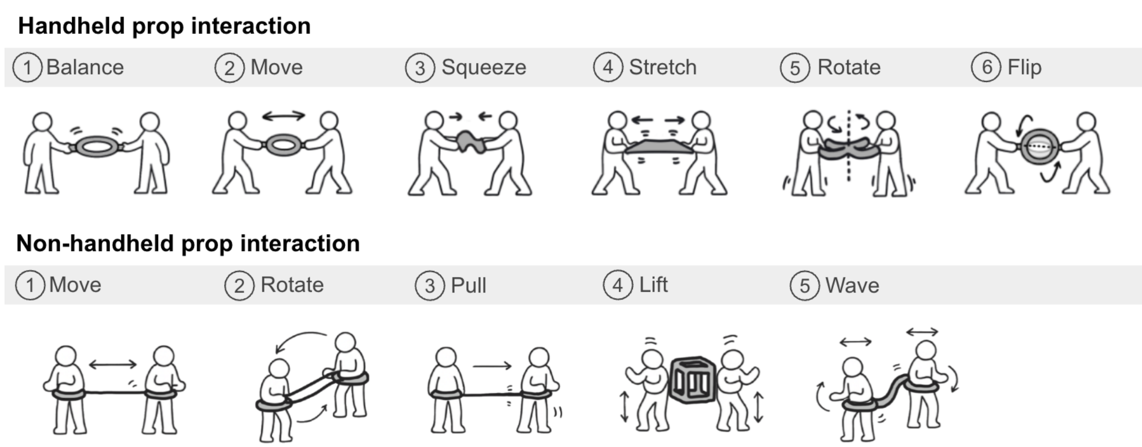

Figure 5: Interaction primitives identified in the workshop. The top row shows six handheld-prop actions—balance, move, squeeze, stretch, rotate, and flip. The bottom row shows five non-handheld-prop actions—move, rotate, pull, lift, and wave.

(1) *Move.* Translating the prop (e.g., G4, G5, H3, I1, J5) or moving closer/farther apart (e.g., F1, H1, I2), which supported *synchronized* walking or *complementary* gait adjustment.
(2) *Rotate.* Orbiting around anchors or each other (e.g., F4, F5, G3, H4, I3, I4), which demanded *synchronized* pacing.
(3) *Stretch.* Creating tension where one player pulls while the other resists (e.g., F2, F3). This was inherently *complementary*, often creating leader–follower roles.
(4) *Lift.* Jointly lifting or lowering a bulky or suspended object (e.g., G2, J4).
(5) *Wave.* Swaying or rippling long, flexible props (e.g., G1, H2, H5, I5). This encouraged rhythmic actions and required a combination of flexibility and scale not present in the handheld designs.

In addition, the surface-shaped Prop J enabled interaction modes not seen in other designs. It supported *platform*-style interactions, where players stood on (e.g., J1, J2), as well as *shelter*-like interactions that involved raising or lowering the sheet to create a shared micro-space (e.g., J3, J4).

3.6 Results and Findings: Reflective Participant Preferences

To prompt participants to reflect deeply on the qualities of each prop and its associated interactions, we asked them to compare each prop–interaction pair along structured aspects.

For each prop, participants reflected on four attributes: *interactivity* (how clearly they could feel or perceive their partner's input), *versatility* (how many interactions or mappings it could support), *creativity* (how original the concept felt), and *simplicity* (how easy it was to understand and operate). For each interaction, they evaluated three attributes: *collaboration* (the degree of synchronized or interdependent action required), *playfulness* (how entertaining or game-like it felt), and *ease of use* (how intuitive and straightforward it was to perform).

To support evaluation, participants ranked each attribute from 1–5. We treated these rankings as formative prompts rather than definitive measures—they helped structure participants' reflections and guide follow-up interviews. Although inferential summaries are provided in Appendix A, our analysis centers on the qualitative insights that informed our selection of interaction concepts for Study 2.

We then synthesized participants' verbal justifications using the deductive framework introduced in Sec. 3.3.1, organizing the feedback into three key attributes—Collaboration, Playfulness, and Ease of Use. These dimensions capture participants' reflections on both the props and the interactions they enabled.

Collaboration. Participants often suggested higher collaboration with actions requiring *"precise, moment-to-moment synchronization"* [P1, P3-4]. For Prop C (the ring-with-handles design), the balancing interaction (C1) was the most preferred. As P2 noted, *"Our movements needed to stay synchronized to keep balance."* Similarly, rotational actions (e.g., C3, D3) were also favored: *"The rotation only worked when we communicated first"* [P4]. Conversely, non-mirrored motions like the stretching in B3 were less preferred for collaboration, as they created an uneven dynamic where *"one player's movement strongly influenced the other"* [P3]. For Prop H in the non-handheld set, the tethered moving task (H1) was the most preferred. *"The two players are not affected by each other's actions, so each must know what they need to do... after a short period of adaptation, they can develop a sense of coordination"* [P6]. This suggests that the collaboration here relied on a shared mental model rather than the physical link itself.

Playfulness. Participants noted that playfulness often emerged when interactions invited *"imaginative scenarios"* [P1, P4] or *"supported creative expression"* [P5, P8]. For Prop D, the handheld rotation interaction (D2) was the most favored. P7 attributed this to the design's evocative nature: *"This interaction immediately made me think of possible gameplay, such as using rotation to transport a small character."* Other primitives like stretching and twisting (e.g., B3, B4, D4) were also praised for evoking real-world fun, *"The squeezing felt like it could map to many fun interactions from real life"* [P1]. Among non-handheld props, for Prop J, the rotational coordination task (J1) emerged as the clear favorite. P8 described this interaction as evoking *"nostalgic fun"*, comparing it to childhood games where one pretended *"not to fall into the lava"* [P8].

Ease of Use. Participants suggested that designs leveraging *"familiar, everyday movements"* [P3, P5] were perceived as more intuitive. For Prop C, the balancing task (C1) was again the most favorable interaction. P1 likened the motion to *"keeping water from spilling in real life"*. and *"Balancing movements were very intuitive"* [P4]. In contrast, props with ambiguous affordances were often less preferred. The oversized Design E, for example, was consistently rated as difficult; *"I couldn't easily connect these actions to how they should be performed"* [P9], suggesting participants attributed this difficulty to a lack of clear collaborative signaling. A similar pattern was observed with non-handheld props, where abstract lifting tasks (G4, G5) were less preferred because the form *"didn't feel intuitive"* [P7] for the task. These findings suggest that ease-of-use preferences aligned with the clarity of a prop's physical affordances, with familiar movement patterns rated most favorably.

3.7 Results and Findings: Prop Properties Shaping Interaction Experience

Across the workshop, participants emphasized that their experience was shaped not only by the actions they performed, but by the props' physical properties. Through our inductive analysis (Sec. 3.3.1), we identified two latent themes, affordance and cooperative experience, that consistently influenced how smoothly players could grasp the prop, infer its intended actions, and coordinate their movements.

3.7.1 How Prop Properties Shaped Affordance.

Prop-Body Orientation. Participants frequently described Props A, C, and D as *"easy to grab"* [P5] and *"approachable from any side"* [P8]. As P3 noted of Prop C, the ring-with-handles design *"offered more places to grab"*, removing the need to identify a correct orientation. These comments pointed to a shared structural feature: all three props exhibit radial symmetry, appearing the same when rotated around their center, allowed players to engage the prop from any angle without negotiation. As P7 mentioned, *"It (Prop A) was immediately obvious where to hold on both sides"*, and players naturally positioned themselves opposite each other around a shared axis. For non-handheld props, participants similarly relied on bilateral symmetry to determine where to stand or anchor their bodies; *"Because both of our bodies were constrained by the prop, the symmetry made it easier for us to coordinate"* [P6].

Prop-Body Contact Points. Participants also suggested how certain handheld props, such as C, D, and E, *"made it clear"* [P2] where to place their hands and how to position their bodies. For Prop C, the internal crossbar *"made it immediately clear which side was mine"* [P4]. These handles provided explicit contact points that, combined with bilateral symmetry, gave each player an obvious side and supported coordinated roles and positioning.

In contrast, Prop B had bilateral symmetry but lacked salient handles or a clear axis, make it *"felt awkward to grab"* [P1], and offer fewer clear shared reference points, leading to uncertainty about where to grasp or how to align their bodies. A similar pattern appeared in non-handheld designs. Participants immediately understood how to use Props F, H, and I, two rings with a connection in the middle, *"you can tell at a glance that it goes around the waist"* [P7], because their coupling points were apparent. By contrast, Props G and J offered few cues for joint engagement, leaving participants *"uncertain about how it was supposed to be used"* [P8].

Fine vs. Gross Motor Skill. Participants emphasized that the prop's scale shaped the granularity of interaction. Smaller handheld props, like C, constrained players to hand movements, *"the interaction required more delicate control"* [P2], supporting fine-grained actions such as twisting, squeezing, or rotating. In contrast, the large ring (Prop A) allowed players to step inside and reposition their bodies around it, making whole-body translations or tilting feel more natural. Non-handheld props, generally larger in size (F, H, I, J), further expanded the available movement space. Prop J, a large cloth, *"immediately hinted that you could move around in a much bigger area"* [P5]. These size-based cues helped players quickly converge on appropriate joint actions, indicating that scale strongly shaped the granularity and scope of interaction.

Constraints as Guidance vs. Ambiguity as Exploration. Participants noted that simple geometric forms (A, B, C, G, J) offered a higher degree of freedom and invited multiple possibilities: *"the ring shape of Prop C feels more flexible, and lets us imagine different kinds of moves"* [P1], while Prop J's cloth *"allowed a huge variety of ways to play"* [P9]. This resonates with Gaver's concept of ambiguity as a resource [28], where interpretive openness supports diverse uses. However, participants also remarked that *"the board (Prop B) was so simple, it was hard to imagine what we were supposed to do with it"* [P8], indicating that minimal structure can provide too few cues and make intended actions harder to envision. In contrast, more articulated designs like Prop E, with its ground-based cross-shaped rod, provided clear cues: *"very direct, almost like imagining how a sail should move"* [P7], offering clearer mappings between form and action. Yet they also pointed out the limits: *"the ways you can play become more restricted"* [P3]. This pattern reflects Norman's account of physical constraints [55]: stronger constraints clarify intended actions but reduce opportunities for exploration. Taken together, these findings suggest a design trade-off: while specific, constrained affordances guide interaction more clearly, ambiguous, open-ended affordances support a broader range of creative actions.

3.7.2 How Prop Properties Shaped Cooperative Dynamics.

Haptic Feedback as Communication Channel. Participants noted that smaller props, such as B and C, were easier to coordinate with because they could more clearly feel each other's movement. P1 noted of Prop C, *"I could sense their hand motion when squeezing the ring"*. These tighter forms amplified subtle haptic cues, helping players read their partner's intent. In contrast, larger props like A, G, and J supported broader, whole-body coordination but offered less precision—Prop G *"worked as long as we walked in the same direction, but I didn't really feel their force"* [P2]. This suggests that the prop scale shaped the tightness of physical coupling, affecting how clearly force was transmitted and how easily players could read each other's actions. Participants also described that material and structural rigidity shaped the distinctness of haptic cues: *"if it (Prop A) were made of something harder, it would affect the other person much more"* [P3]. Prop H, with its foam-rod connector, *"made it easy to feel what the other person was doing"* [P8], offered much more pronounced axial feedback than Props F or I, even though they shared similar ring-and-connector geometries. However, this clarity introduced constraints. Prop E, the most rigid design, was described as *"over-specified and constrained, with a very limited range of movement"* [P7], offering strong tactile feedback but limiting the variety of actions players could perform. Conversely, participants highlighted that props made from more pliable or elastic materials felt more versatile and open-ended. Prop D, the X-shaped prop, was *"the most diverse, supporting many different rules"* [P10], and Prop F's elastic band *"expanded the interaction range… which increased possibilities"* [P3]. But this flexibility might weaken mutual sensing *"When (Prop D) one side moved, the other didn't really feel it"* [P9]. Together, these observations reveal a trade-off: rigid structures enhance force transmission but constrain action possibilities, while flexible ones broaden expression but reduce haptic feedback.

Visual Cues as Communication Channel. Although haptic cues were central for inferring intentions, visual information also supported coordination. Handheld props often positioned players face-to-face, letting them see each other's gestures and anticipate actions: *"with Prop A, I would mirror my partner's posture to cooperate more effectively"* [P5]. In contrast, non-handheld props frequently placed players back-to-back (Prop G) or facing outward (interactions in Props F, H, and I), removing direct visual access. Without these cues, coordination became more challenging and sometimes felt disconnected: *"it felt like we were each doing our own thing rather than cooperating"* [P1].

3.8 Design Implications

Beyond individual device forms or actions, shared props shaped cooperative play through three overarching dimensions: embodiment, interaction type, and coordination mode. These dimensions emerged across both handheld and non-handheld designs and reflect how physical form and manipulation structure social dynamics.

Embodiment (handheld and non-handheld, scale and locus of control). Props varied in both form and control. Handheld props enabled fine-grained, tactile coordination, while non-handheld props required full-body movement and spatial alignment. Scale further shaped control: larger props emphasized gross motor synchrony, often resulting in looser coupling, while smaller props supported precise, hand-based actions. Together, these factors influenced how players perceived partner input and maintained coordinated rhythms.

Interaction Type (manipulation primitives). The interactions were clustered around a small set of primitives: moving, rotating, squeezing, stretching, and flipping. Movements mapping to everyday embodied experience were described as *"easy to define and understand"* [P1], lowering entry barriers. Props that support multiple primitives were rated more playful and versatile, sustaining variety throughout sessions.

Coordination Mode (mirrored vs. complementary). Props shaped how effort was distributed between players. Mirrored coordination (synchronized actions like balancing or rotating) felt predictable and fair, and was often rated as the most balanced form of collaboration. In contrast, complementary coordination required players to take on distinct but interdependent roles. This was clearly observed in interactions like stretching (B3) and pulling (F2, F3), which often created an uneven but engaging leader–follower dynamic that required more communication to succeed. Props that supported shifts between these modes enabled more flexible collaboration.

Together, these three dimensions offer design implications for shaping physical co-op experiences, highlighting how shared props mediate teamwork through perception, communication, and coordination. Drawing on these insights, we developed an MR prototype that instantiates these ideas and conducted a user study to compare the experience of physical co-op play against a virtual co-op baseline, as described in the following sections.

4 STUDY #2: USER EXPERIENCE STUDY

To understand differences between PHYSICAL CO-OP and VIRTUAL CO-OP collaboration, we conducted a user experience study building on the broad design space generated in Study #1. Our goals were to explore how the two conditions shape user experience and cooperative behavior, specifically: 1) While performing the same cooperative task, how does the experience of a physical co-op game differ from a virtual co-op one across key metrics (e.g., collaboration, enjoyment, safety)? 2) How do observable cooperative behaviors, such as communication and physical coordination, differ between the conditions?

4.1 Study Design

We conducted a within-subjects study in a shared physical space, where participants played the same MR co-op game under two conditions: a PHYSICAL CO-OP condition featuring shared props and controls, and a VIRTUAL CO-OP baseline using separate props and controls. We assessed participants' experiences through subjective metrics (spatial safety, collaboration, engagement, enjoyment, sense of achievement, and overall preference), behavioral observations (collisions, near-misses, task-related verbal communication, and deictic expressions), and qualitative reflections. Subjective judgments were collected using a 10-point strength-of-preference framework [24] to capture both preference and its perceived magnitude. Behavioral events were recorded on video and annotated using a predefined behavioral codebook, with differing interpretations resolved through discussion to reach a shared understanding. Post-scenario reflections were gathered through brief semi-structured interviews and later examined using a reflexive thematic approach [11]. This study was reviewed and approved by our institution's ethics board, and details of the analytic procedures appear in Section 4.5.

4.2 Prototype Design: From Workshop to Gameplay

To create a robust testbed for comparison, we translated our workshop findings into a playable MR prototype. The theme and initial concept for our game were inspired by early explorations in this domain, such as the *Wandering Spirit* [74] project, which introduced the idea of a shared flexible loop for MR co-op play. Based on the insight from Study 1, we selected the most representative interaction types and prop shape, and refined them into a unified gameplay scenario. We also aligned the VIRTUAL CO-OP baseline with the PHYSICAL CO-OP goals and interactions to ensure a controlled comparison.

4.2.1 Prop Design.

Building on insights from the workshop—where symmetric, handheld props with clear affordances were consistently rated as most supportive for collaboration and ease of use—we adopted Prop C as the foundation and iteratively refined it into the ring-shaped prop (Ø 45 cm) used in this study. The final symmetric form supports mirrored actions (e.g., squeezing, rotating) and synchronous joint movements, while its moderate scale promotes coordinated interaction with room for fine individual adjustments. The simple geometric structure remains task-agnostic and intuitive, enabling versatile, low-overhead engagement. A compliant foam shell over a fiberglass skeleton, combined with clearly marked grasp nodes, provides multiple stable handholds, facilitates rapid role switching, and ensures reliable haptic transmission of intent.

4.2.2 Interaction Design.

From the workshop's emergent primitives, we selected the four most highly rated and commonly proposed interactions for our game: moving, balancing, squeezing, and rotating. These interactions were chosen because they directly map onto two core coordination dynamics we observed: full-body alignment (moving, balancing) and temporal synchronization (squeezing, rotating), requiring both continuous micro-adjustments and precisely timed joint actions.

4.2.3 Co-op Gameplay Design.

Figure 6 maps MR co-op into four quadrants. Within VIRTUAL CO-OP, players may operate a shared virtual object (figure 6.a) vs. separate virtual objects (figure 6.b). To understand player experiences, we implemented and piloted both conditions with eight users (4 male, 4 female; ages 22–27). Pilot participants reported that the experience PHYSICAL SEPARATE PROPS × VIRTUAL SHARED OBJECT condition was significantly worse due to the following limitations:

- ***Lack of physical bond.*** Without a shared physical prop, jointly holding and manipulating a shared virtual object was challenging. For example, when players attempted to flip a virtual object together, one player might begin the flip while the other remained still, unaware of the partner's movement. Because the system must commit the shared virtual object to a single state, this created instability or "breaks" in the joint action.
- ***Reduced visual coordination in MR.*** In MR, players need to focus visual attention to the direction of movement, environment, and tasks, resulting in reduced visual attention on the prop or on their partner. The reduced visual attention on their partner made maintaining a shared virtual object challenge in MR, compared to non-MR games where their partner's avatar are always clearly visible (e.g., moving a virtual sofa together in *Moving Out).*

Based on pilot feedback, the PHYSICAL SEPARATE PROPS × VIRTUAL SEPARATE OBJECTS condition was selected as the baseline.

Game Scenarios. We implemented a space-station–themed MR game designed to evaluate cooperative interactions using a ring-shaped prop. Players worked together to transport virtual spirits

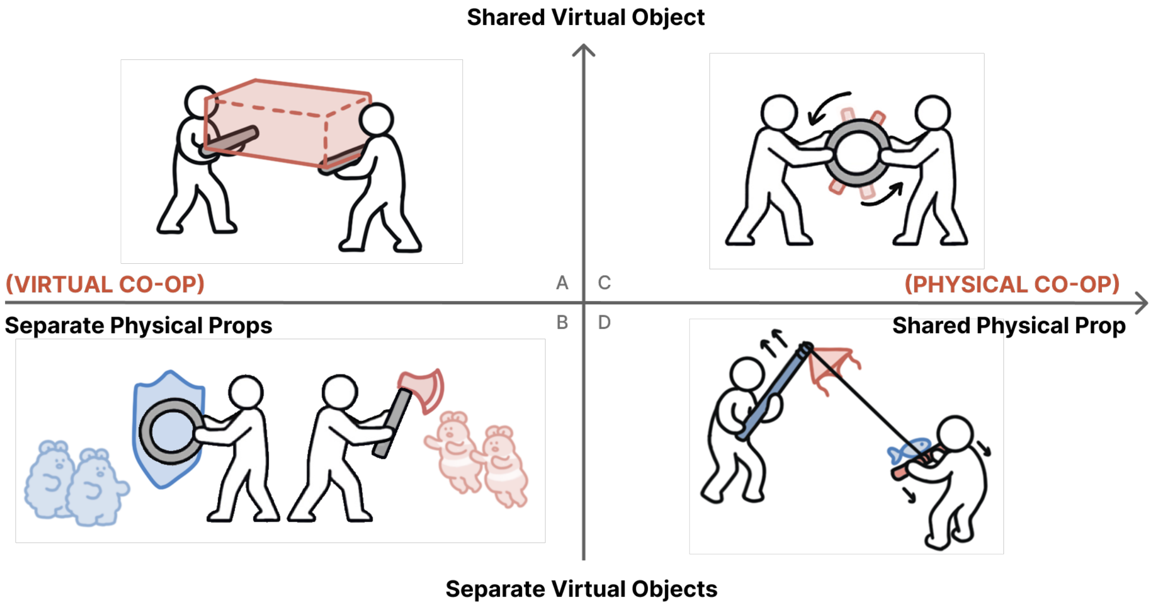

Figure 6: Design space of mixed-reality (MR) co-op play, organized by whether partners use separate vs. shared physical props (horizontal) and act on separate vs. shared virtual objects (vertical). The physical co-op side (right) centers on jointly held MR props that provide continuous haptic coupling, allowing partners to sense each other's bodily movements and co-adjust actions through the shared physical medium. The virtual co-op side (left) lacks this physical channel: the upper-left quadrant requires partners to coordinate solely through the dynamics of a shared virtual object, while the lower-left quadrant reflects MR play where partners handle separate props and separate virtual objects, aligning goals without shared control.

from a starting point to a designated goal within a 3 m × 5 m living-room–sized area. The game comprised two scenarios, each instantiating a distinct pair of the four target interaction types—moving, balancing, squeezing, and rotating.

- ***Trampoline Scenario.*** This scenario instantiated moving and balancing interactions. Players used the prop as a trampoline-like surface to guide spirits toward the goal, either by repositioning the prop to catch falling spirits or by maintaining balance to carry rolling spirits without letting them slip off.
- ***Bubble Scenario.*** This scenario instantiated squeezing and rotating interactions. Players first squeezed the prop to generate bubbles that encapsulated the spirits and then rotated the prop to activate virtual airflow that propelled the bubbles toward the destination.

Across both scenarios, the two conditions shared identical goals, timing, and task structure. The physical co-op condition required players to manipulate a shared physical prop linked to a shared virtual object, creating continuous bodily coupling. The baseline condition used separate physical props and separate virtual objects, enabling players to perform the same interaction sequence without haptic or spatial coupling. This allowed us to isolate the effects of shared physicality while keeping all other task parameters constant.

4.3 Participants

We recruited 8 pairs of participants (n=16, 11 female, 5 male), aged 19–28 (M = 22.9, SD = 2.16). We specifically recruited established pairs (friends, siblings, partners) rather than "ad-hoc" pairs of strangers, to control for the variability of initial social awkwardness or "ice-breaking" effects. By studying pairs with an existing rapport, we could more directly focus on how the interface affected their established coordination and communication strategies, rather than observing the process of two strangers learning to work together. Regarding VR/MR usage, 3 reported no prior use, 7 reported rare use (≤ once per year), 2 reported occasional use (about once every three months), and 4 reported frequent use (≥ once per week). Participants received a nominal compensation for their participation.

4.4 Study Procedure

After introducing the experiment procedure and addressing participants' questions, participants engaged in two gameplay scenarios, each lasting 15 minutes and including both the PHYSICAL CO-OP condition and the VIRTUAL CO-OP condition, with counterbalancing applied to both the ordering of gameplay scenarios and the ordering of conditions to mitigate sequence effects across participants. Participants wore a Meta Quest 3 headset to view the mixed-reality scene and operated a ring-shaped physical prop instrumented with Quest 3 controllers. Each condition began with a short practice round to allow participants to warm up. After each scenario, participants completed an 8-minute questionnaire and took a 2-minute break. During each condition, participants' task performance and interactions were recorded via video and system logs, and later analyzed through video coding to annotate collisions, near-misses, and

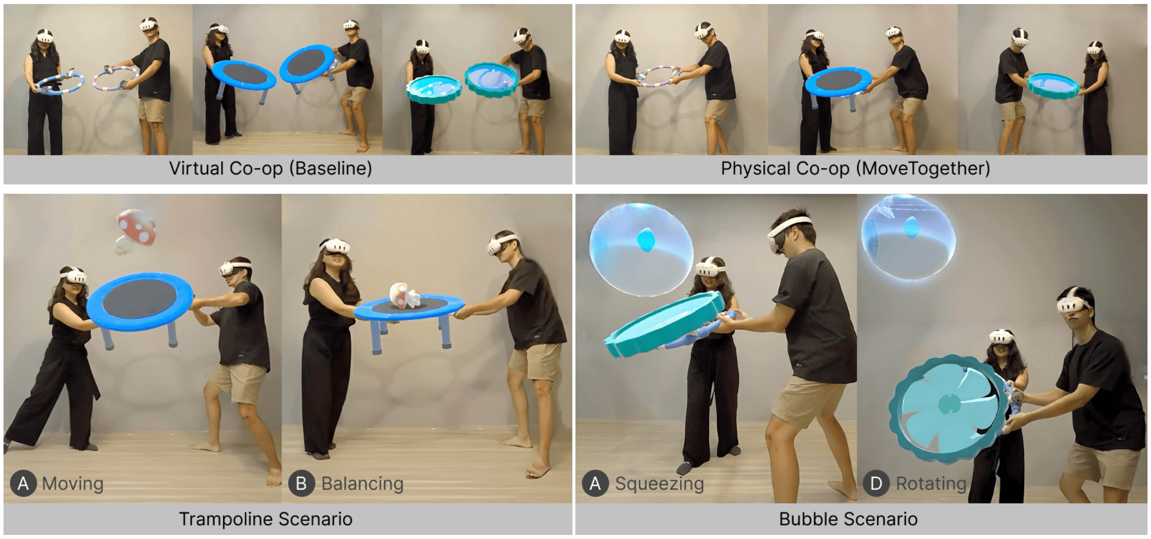

Figure 7: Study 2 conditions and gameplay scenarios. Top row: The study compared two cooperative conditions. In the Virtual Co-op (Baseline) condition, players each held a separate physical prop and interacted with separate virtual objects, coordinating only through visual and verbal cues. In the Physical Co-op (MoveTogether) condition, players jointly held a single physical prop to manipulate a shared virtual object. Bottom row: The two gameplay scenarios, counterbalanced across participants, each included two task types. The Trampoline Scenario featured (a) Moving and (b) Balancing, while the Bubble Scenario involved (c) Squeezing and (d) Rotating.

communication behaviors. Upon completing both scenarios, participants engaged in a semi-structured interview to reflect on their experiences. The study duration was approximately 60 minutes.

4.5 Results and Findings

For subjective responses (Figures 8 and 9), we analyzed participants' comparative judgments using the 10-point strength-of-preference framework [24]. In this method, participants first selected which condition they preferred for each metric (e.g., "Collaboration") and then indicated the magnitude of that preference on a 5-point difference scale (1 = very slight, 5 = very strong). We encoded responses on a signed -5 to +5 scale, where -1 to -5 indicates increasing preference for the virtual condition and +1 to +5 indicates increasing preference for the physical condition (0 is not available as a response option). Given the ordinal nature of these ratings, we applied a one-sample Wilcoxon signed-rank test to assess deviations from the neutral midpoint (0), an established nonparametric choice for preference-difference data [15, 61, 68], and is consistent with previous studies employing similar analytical frameworks [48, 73, 75]. Effect sizes [62] were computed as $r = Z/\sqrt{n}$, following conventions in ordinal preference analysis. Behavioral observations—including collisions, near-misses, and directional cues—were coded using a predefined codebook. Two researchers jointly reviewed the recordings and resolved differing interpretations through discussion, providing contextual grounding for the qualitative themes.

For qualitative data, we conducted Reflexive Thematic Analysis (RTA) [11]. Two researchers reviewed the interview transcripts and video materials to generate initial codes and gather illustrative quotations. They iteratively compared and refined these codes, revisiting the transcripts and recordings to develop and consolidate themes. This reflexive process emphasized participants' interpretations of their collaborative experience, with behavioral observations serving as contextual anchors that informed theme development. When uncertainties or divergent interpretations emerged, the researchers resolved them through discussion to reach a shared analytic understanding.

4.5.1 Physical Co-op Fostered Tighter and More Vocal Collaboration. Across both scenarios, participants rated physical co-op as significantly more collaborative (Trampoline Scenario: 94% preference strength, $p < .001$, $r = .90$; Bubble Scenario: 81% preference strength, $p < .01$, $r = .80$). This was supported by behavioral observations (Figure 10), where task-related verbal cues increased by about 2.4 times (from 42 to 101), and directional cues increased by about 3.4 times (from 44 to 149).

Qualitative feedback revealed this heightened sense of collaboration stemmed from two key factors:

Finer-Grained Coordination. Physical co-op was associated with fine-grained, moment-to-moment coordination, which participants described as *"moving as one"* [P1, P6, P8, P10, P13, P15, P16]. As P8 put it, *"Doing the same action together feels more collaborative."* In contrast, the virtual baseline encouraged a coarser *"division of labor"*, where players would partition roles and work in parallel rather than in continuous synchrony [P4, P5, P11, P12].

Denser Communication. Physical co-op elicited denser, multimodal communication compared to the virtual baseline, where speech primarily covered hand-offs and reminders [P4, P5, P12]. In the physical co-op condition, players combined constant verbal cues with embodied, non-verbal signals perceived through the prop [P3, P6, P8, P9, P10, P13]. P10 described this synergy as immediate: *"At every moment we synchronize the goal and method."* However, participants also cautioned that the prop was not a substitute for

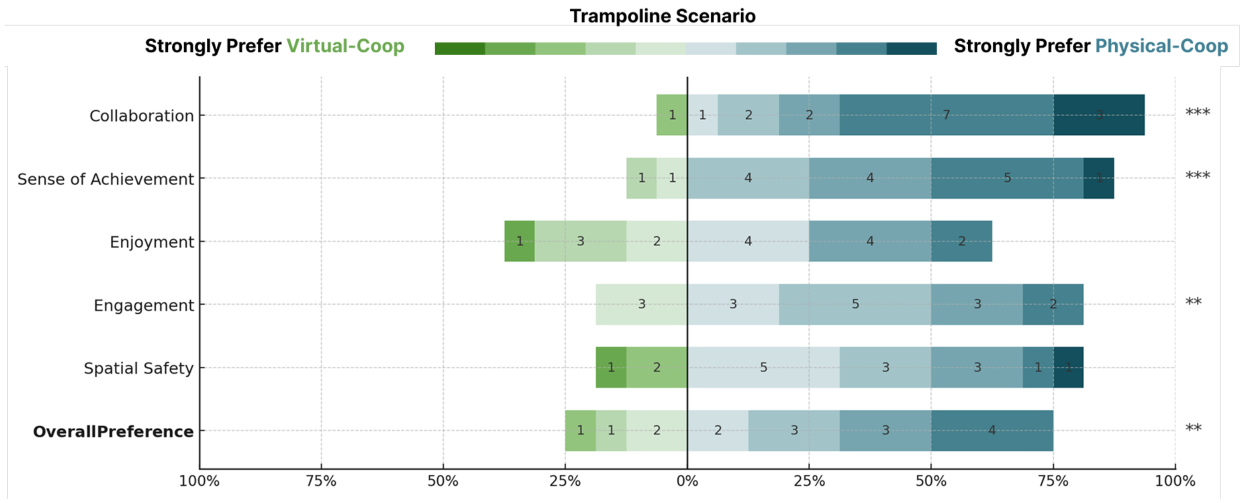

Figure 8: Preference rating on a 10-point scale in Trampoline Scenario. Participants significantly preferred physical co-op for Collaboration (p < .001), Sense of Achievement (p < .001), Engagement (p < .01), and Overall Preference (p < .05).

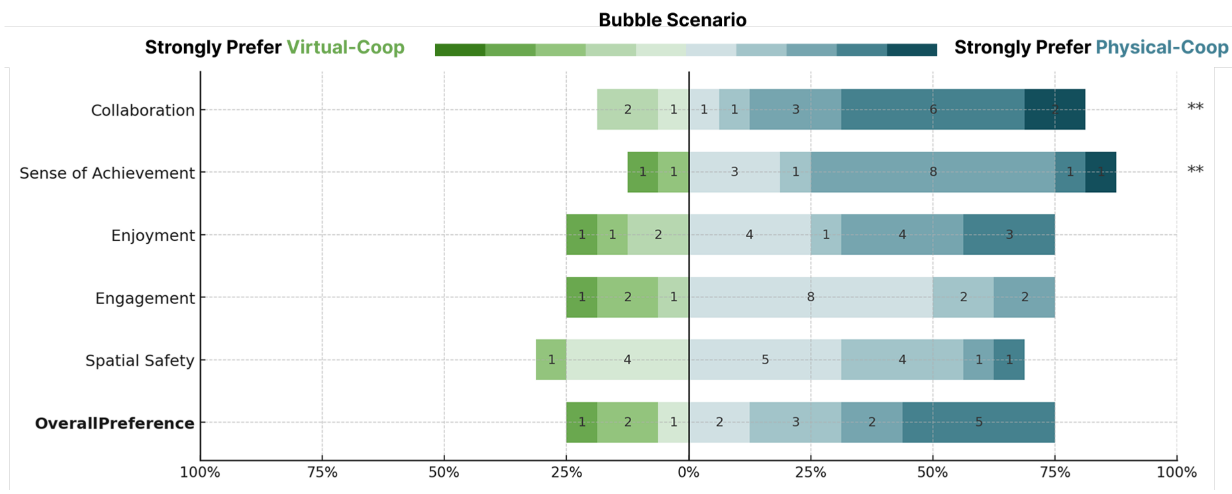

Figure 9: Preference rating on a 10-point scale in Bubble Scenario. Participants significantly preferred physical co-op for Collaboration (p < .01) and Sense of Achievement (p < .05).

talk; as several noted, *"just pulling without talking"* significantly reduced coordination quality [P3, P7, P10, P13].

4.5.2 Physical Co-op Increased Sense of Achievement and Engagement. Participants reported a significantly stronger sense of achievement in the physical co-op condition across both scenarios (Trampoline Scenario: 88%, $p < .001$, $r = .81$; Bubble Scenario: 88%, $p < .05$, $r = .58$). Engagement was also significantly higher in the Trampoline Scenario (81%, $p < .01$, $r = .74$).

Participants explained that in the physical co-op condition, achievement felt collective. Success was framed as *"we did this together"*, with a stronger sense of *"joint completion"* [P2, P3, P8, P15]. As P2 said, *"Scoring together feels more rewarding."* Engagement in physical co-op was often attributed to the demanding nature of the coordination itself. As P7 noted, *"We had to coordinate every move, which kept me focused."* Enjoyment in physical co-op often came from the shared challenge and the feeling of *"playing the same game together"* [P1, P3, P10, P15, P16].

4.5.3 Physical Co-op Enhanced Spatial Safety. After establishing the collaborative and experiential benefits, we also found that physical co-op dramatically improved spatial safety. Behavioral coding (Figure 10) revealed that people collisions decreased by about 91% (from 21 to 2), and people near-misses were eliminated entirely (from 31 to 0). Total collisions were reduced by about 53% (from 34 to 16), and total near-misses decreased by about 93% (from 44 to 3).

Across both scenarios, participants reported feeling somewhat safer in the physical co-op condition, though this trend did not reach statistical significance (Trampoline Scenario: 81%, $p > .05$, $r = .41$; Bubble Scenario: 69%, $p > .05$, $r = .41$). Participants nonetheless described why the physical prop felt safer, noting that the shared prop acted as a physical link that aligned their motion. Several described *"moving together"* along the *"same path"* and exercising

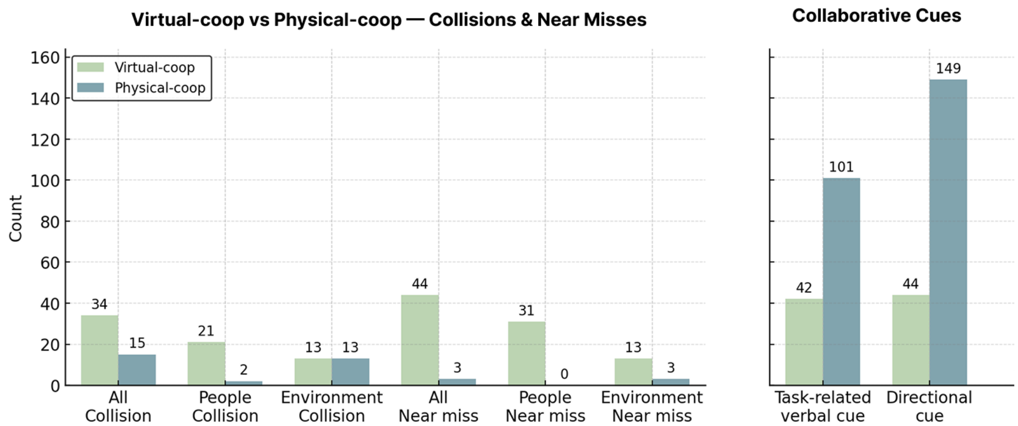

Figure 10: Behavioral coding results comparing the virtual co-op and physical co-op conditions. The left panel shows the number of collisions and near-misses, separated into person–person and person–environment events. The right panel shows the frequency of collaborative cues, including task-related verbal cues and directional cues.

"mutual restraint" [P3, P4, P5, P11, P13, P15]. As P11 stated, *"When we move together, our paths are the same, so we don't collide."*

4.5.4 Overall Preference. Reflecting these cumulative benefits, participants showed a significant overall preference for physical co-op in Trampoline Scenario (75% preference strength, $p < .05$, $r = .59$), with a similar but non-significant trend in Bubble Scenario. The preference often came down to a trade-off. Many favored physical co-op for its *"cooperative feel"* and shared emotion, with P16 stating, *"It feels like we're truly playing the same game together."* Others preferred the VIRTUAL CO-OP baseline for the autonomy and precise individual control it afforded [P9, P11].

5 DISCUSSION

This work introduced PHYSICAL CO-OP, a gameplay mechanic that externalizes teamwork to a shared, tangible prop. In this section, we discuss how PHYSICAL CO-OP bridges the sensory gaps inherent in MR (Sec. 5.1), map interaction primitives to specific gameplay goals (Sec. 5.2), and propose strategies for mediating player asymmetries in physically coupled play (Sec. 5.3).

5.1 Bridging the Communication Gap in MR through a Shared Physical Channel

A substantial body of work shows that people naturally coordinate their actions through three primary channels: visual [32], audio [19], and haptic communication [64]. Cooperative digital games have long leveraged the first two, using visual attention cues (e.g., avatar motion [2], gaze indicators [58, 84]) and spoken commands [71], yet the haptic, embodied physical channel remains comparatively underexplored. In contrast, many real-world cooperative activities rely heavily on kinesthetic communication, where partners implicitly read each other's forces and movement intent [27], and on physical constraints that bind partners into a single coupled body (e.g., three-legged races). These forms of physical coupling remain largely unexplored in co-located digital play.

Our findings build on the Bodily Interplay framework proposed by Mueller et al. [52], particularly their category of Interdependent Exertion: Shared Object. Whereas prior work examined shared-object exertion primarily in traditional or screen-based settings, our work extends this concept into an MR, first-person context where the usual communication channels are altered. Mixed reality reshapes how players access visual and verbal cues: the limited field of view of VR/MR headsets restricts peripheral vision [77], making it difficult to see a partner's body orientation or gaze unless directly facing them. As a result, visual grounding for spoken instructions becomes harder [36]—players may "hear" a command but lack the visual scaffolding needed to interpret it. This constraint makes shared-object interdependence newly consequential, because physical coupling introduces a haptic communication channel that can offset these sensory limitations.

Our study shows that the shared prop effectively fills this sensory gap by augmenting coordination via the visual channel with kinesthetic communication through the body. Because participants had to visually track virtual objects (e.g., falling spirits or drifting bubbles), they could not continuously monitor their partner. Instead, the prop provided a continuous kinesthetic signal that conveyed intention: subtle pulls indicating direction changes, or resistance indicating hesitation, thereby offloading coordination away from vision and into haptics. Furthermore, the physical constraint of the prop forced players to act as a single unit. This interdependence likely contributed to the significantly higher "Sense of Achievement" and "Engagement" observed in our study, as success required a tangible form of "joint completion" impossible in the virtual condition.

Interestingly, the presence of haptics did not reduce verbal communication. Instead, physical co-op produced more verbal cues (Fig. 10). Rather than replacing speech, haptics appeared to scaffold it. In the presence of haptic feedback, participants found verbal communication more beneficial, using it to clarify the ambiguous forces they were feeling.

However, our observations also show that the haptic channel is not always beneficial—it depends on how dyads integrate it with other modalities. Effective pairs used all three channels in complementary ways. Vocal cues were commonly served as anticipatory signals (*"slowing down"*, *"I'm turning left"*), while visual and haptic cues functioned as supplementary confirmations that helped players adjust timing, direction, or force. These multimodal strategies enabled smoother, more synchronized joint action. In contrast, pairs that struggled with collaboration tended to rely on only a single channel. Heavy reliance on haptics alone—such as pulling the shared prop without warning—often produced abrupt, unexpected movements that disrupted coordination. Conversely, exclusive reliance on speech made it hard to convey spatial nuance or subtle adjustments in force. These patterns illustrate that in co-located MR, the shared prop is most effective when used to balance communication, anchoring abstract verbal plans in concrete physical actions.

5.2 Interaction Types in Co-op Game Design

Synthesizing insights across both studies, we outline our key findings on how different interaction primitives shape cooperative gameplay experiences. Participants repeatedly described ***large-scale movements*** as *"immediately intuitive"* [P3], echoing Study 1's identification of moving, balancing, rotating, and squeezing as core primitives. This aligns with prior research showing that gross motor and nonverbal actions, such as gestures and shared bodily orientation, facilitate coordination in co-located play [49], and that steering and movement constitute core interaction tasks that are easy to learn and synchronize [43]. These interactions allow teams to coordinate with minimal explanation and are well-suited for onboarding in genres relying on shared steering and co-orientation, such as *cooperative racing* or *sports simulations.*

Fine-motor interactions were consistently described as *"the hardest to coordinate"* [P7, P8], reinforcing that rotating or angle-sensitive tasks carry steeper learning demands. Prior work similarly shows that fine-grained motor control demands high precision, where small errors greatly impact performance [23]. Even small misalignments disrupted joint action—*"a tiny mistake throws us off immediately"* [P9]—making these interactions better matched to precision-based genres where shared spatial reasoning is essential, such as *tactical shooters* or *cooperative puzzle games.*

Timing-dependent actions revealed another distinct pattern, with participants noting that *"we had to time our force exactly together"* [P1]. Because success hinged on synchrony, teams naturally increased verbal coordination—*"we had to talk more to sync every beat"* [P2]. This behavior reflects the necessity of sustaining a shared temporal rhythm, a process requiring partners to continuously adapt to each other's timing [81]. These timing-sensitive primitives are strong candidates for genres that depend on rhythm and temporal alignment, such as *rhythm games* or *cooperative cooking simulators.*

While physical co-op already leverages rich nonverbal channels such as haptic coupling and shared force feedback, lightweight digital cues may further ease coordination. Integrating CSCW principles—such as shared visibility patterns [54] or lightweight intent signaling [22]—could help teams manage more complex or asymmetrical roles, extending the design opportunities available in *cooperative MR play.*

5.3 Mediating Player Asymmetries in Embodied Play

A key challenge we observed is that shared physical props can amplify player asymmetries. Participants frequently noted that differences in *"height and movement speed"* [P3–P4, P11–P12] or *"skill level"* [P3–P4, P5–P6, P11–P12] made cooperation harder, with one participant explaining that they sometimes felt *"dragged around by the other person"* [P11]. Conversely, more proficient players described moments of feeling *"held back"* [P6], illustrating how shared-prop coupling can transform even small mismatches into noticeable friction. While curated level design—such as micro-progressions [73]—can help pairs adapt, our findings suggest additional strategies.

Dynamic Difficulty Adjustment. Prior work has explored balancing player skills through algorithmic adjustments [20, 35, 50]. In an MR system, this could involve actively mediating the interaction's physics. For example, if one player is stronger, the system could introduce virtual "resistance" on their side of the prop to balance the forces. If one player is more skilled, the game could present them with slightly more complex virtual targets, ensuring both players remain appropriately challenged.

Asymmetrical Roles. Drawing on research into interdependence [9, 30, 56], a game could embrace player differences by assigning complementary roles that are mechanically coupled. For instance, in a canoeing game, one player could be the "engine" (powerful strokes) while the other acts as the "rudder" (fine steering). While less realistic than separate controls, this intentionally trades realism for a higher degree of forced coordination, turning physical differences into a core part of the game's strategy.

5.4 Limitations and Future Work

Our work provides a focused exploration of physical co-op, highlighting several avenues for future research. First, our studies centered on two-player, pre-existing pairs to isolate coordination mechanics and avoid social awkwardness. Future work should examine ad-hoc pairs and larger groups, where new relationship dynamics, control patterns, and conflict resolution emerge. Second, our study design involved a deliberate trade-off: while the round-robin and collaborative discussion structure enriched ideation and ensured coverage of all interaction concepts, it may introduce order and exposure effects. Future work could explore alternative study designs that balance control with creative exploration. Third, we evaluated a single prop: the ring, chosen from our design workshop. Studying other prop types—balancing flexibility, haptic clarity, and other trade-offs—could broaden understanding of the design space.

Finally, our prototype explored one visual modality: a visually co-located MR game where both players see the same shared virtual and physical space. During piloting, we found that the configuration combining separated physical controls with shared virtual objects introduced substantial challenges in MR and was therefore not included in the current study. As a result, our findings reflect the combined effects of shared physical and virtual elements, rather than isolating the contribution of either dimension alone. This highlights a key area for future work: a direct comparison of how different visual and interaction modalities affect collaboration, including configurations with shared physical controls and separated virtual views. Related work, such as Mutual Human Actuation [17], explores shared physical interaction in visually separated VR contexts without explicit co-op gameplay, pointing to complementary directions for understanding how physical coupling and virtual separation shape coordination and experience. A future study could further explore physical co-op configurations with shared physical controllers but separated virtual views, investigating how alternative MR designs might address current challenges while preserving embodied teamwork, haptic coupling, and co-located collaboration.

6 CONCLUSION

In this paper, we introduce MoveTogether, a physical co-op mechanic in which two players jointly operate a single tracked prop, adding a shared physical communication channel on top of visual and audio cues. By embedding collaboration in the physical world, rich nonverbal cues [66, 67], haptic coupling, and mutual constraint become available when partners act on the same object, reshaping how they synchronize, negotiate, and adapt. Our design exploration with professional designers revealed consistent prop dimensions—grasping mode, size, geometry, and material—and interaction primitives that influence affordance and cooperative dynamics, providing a structured vocabulary for reasoning about physical co-manipulation in MR contexts.

Building on these insights, we implemented an MR prototype using a tracked ring-shaped prop to operationalize shared physical control. Our user study shows that physical co-op enabled finer coordination, reduced collisions and near-misses, and encouraged more strategic communication, with participants reporting higher collaboration, engagement, enjoyment, and overall preference. Together, our contributions include: (1) framing physical co-op as a lens for structuring co-located interaction; (2) an MR prototype that demonstrates jointly controlled props; (3) identification of how shared physical communication shapes teamwork in MR co-op play; and (4) open-sourcing our game to support further exploration. We hope this work informs future systems that embed collaboration more directly into the physical world.

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A Appendix A: Inferential Summary

For our inferential analysis, we computed mean ranks (where lower values indicate stronger preference) and conducted separate Friedman tests for the handheld and non-handheld prop sets, as well as individual Friedman tests for the interaction rankings associated with each prop. When an omnibus test reached significance, we followed up with Wilcoxon signed-rank post-hoc comparisons using Holm correction (two-tailed, $\alpha = .05$). In the main text, we report findings only for the three attributes highlighted in our Study 1 Reflective Participant Preferences (Sec. 3.4.3).

A.1 Collaboration

Prop	Interaction 1	Interaction 2	Interaction 3	Interaction 4	Interaction 5
A	2.875	**2.375**	3.625	2.625	3.500
B	3.375	**1.750**	3.750	2.875	3.250
C	**1.5**	3.375	2.375	3.875	3.875
D	3.000	**2.500**	3.250	2.750	3.500
E	**2.125**	3.875	2.875	2.625	3.5
F	**2.000**	2.250	3.375	4.125	3.250
G	**1.375**	2.125	2.625	3.125	4.750
H	**1.875**	2.375	4.125	2.875	3.625
I	**1.500**	2.250	3.375	3.625	4.250
J	**1.375**	2.375	3.250	4.125	3.875

Table 1: Mean ranks for all interactions (A1–J5) on the *Collaboration* measure. Lower values indicate a more collaborative interaction (1 = best, 5 = worst).

Prop	Friedman $\chi^2(4)$	p-value	Top Interaction (Mean Rank)	Interpretation
A	5.52	.238	A2 (M = 2.375)	n.s.
B	7.50	.112	B2 (M = 1.75)	n.s.
C	13.80	.008	C1 (M = 1.50)	Significant omnibus; no sig. post-hoc
D	2.00	.736	D2 (M = 2.50)	n.s.
E	6.20	.185	E1 (M = 2.125)	n.s.
F	10.60	.031	F1 (M = 2.00)	Significant omnibus; no sig. post-hoc
G	21.90	$< .001$	G1 (M = 1.375)	Significant omnibus; no sig. post-hoc
H	10.00	.040	H1 (M = 1.875)	Significant omnibus; no sig. post-hoc
I	16.50	.002	I1 (M = 1.50)	Significant omnibus; no sig. post-hoc
J	13.60	.009	J1 (M = 1.375)	Significant omnibus; no sig. post-hoc

Table 2: Summary of Friedman tests and descriptive top-ranked interactions across all props (A–J) on the *Collaboration* measures. Mean rank: lower is better (1 = best, 5 = worst). "n.s." = not significant. For props with significant omnibus effects (C, F–J), no Wilcoxon pairwise comparisons survived Holm correction.

A.2 Playfulness

Prop	Interaction 1	Interaction 2	Interaction 3	Interaction 4	Interaction 5
Handheld Props (A–E)					
A	2.5	**2.125**	3.50	3	3.875
B	3.25	**2**	3.125	2.75	3.875
C	**1.625**	3.125	2.375	4.125	3.75
D	**2.25**	3.5	2.75	**2.25**	4.25
E	**2.625**	3.125	3	3.125	3.125
Non-Handheld Props (F–J)					
F	**1.5**	2.375	3.25	4	3.875
G	**1.5**	2.375	3.25	4	3.875
H	2.25	**1.375**	4.125	3.375	3.875
I	**1.5**	2.125	3.375	3.75	4.25
J	**1.5**	3.375	2.5	4.25	3.375

Table 3: Mean ranks for all interactions (A1–J5) on the *Playfulness* measure. Lower values indicate more playful interactions (1 = most playful, 5 = least playful). Bold entries represent the most playful interaction within each prop.

Prop	Friedman $\chi^2(4)$	p-value	Top Interaction (Mean Rank)	Interpretation
A	6.50	.165	A2 (M = 2.125)	n.s.
B	6.10	.192	B2 (M = 2)	n.s
C	13.20	.010	C1 (M = 1.625)	Significant omnibus; no sig. post-hoc
D	9.60	.0477	D1/D4 (M = 2.25)	Significant omnibus; no sig. post-hoc
E	0.60	.963	E1 (M = 2.625)	n.s
F	14.30	.0064	F1 (M = 1.5)	Significant omnibus; no sig. post-hoc
G	23.80	<.001	G1 (M = 1.5)	Significant omnibus; no sig. post-hoc
H	17.20	.002	H2 (M = 1.375)	Significant omnibus; no sig. post-hoc
I	16.90	.002	I1 (M = 1.5)	Significant omnibus; no sig. post-hoc
J	13.9	.008	J1 (M = 1.5)	Significant omnibus; no sig. post-hoc

Table 4: Summary of Friedman tests and descriptive top-ranked interactions across all props (A–J) on the *Playfulness* measures. Mean rank: lower is better (1 = best, 5 = worst). "n.s." = not significant. For props with significant omnibus effects (C, F–J), no Wilcoxon pairwise comparisons survived Holm correction.

A.3 Ease of Use

Prop	Interaction 1	Interaction 2	Interaction 3	Interaction 4	Interaction 5
Handheld Props (A–E)					
A	2.75	**2.5**	3.125	2.75	3.875
B	3.75	**2.125**	**2.125**	3.625	3.375
C	**1.5**	3	2.875	3.875	3.75
D	2.875	**2.375**	3.5	2.875	3.375
E	**2.25**	3	3.375	3.125	3.25
Non-Handheld Props (F–J)					
F	**2.25**	**2.25**	3.625	3.875	3
G	**1.5**	2.125	2.75	4	4.625
H	2.25	**1.75**	4.625	3.25	3.125
I	**1.125**	2	3.25	4	4.625
J	**2.125**	3.375	2.75	3.75	3

Table 5: Mean ranks for all interactions (A1–J5) on the *Ease of Use* measure. Lower values indicate more ease of use interactions (1 = most ease of use, 5 = least ease of use). Bold entries represent the most ease of use interaction within each prop.

Prop	Friedman $\chi^2(4)$	p-value	Top Interaction (Mean Rank)	Interpretation
A	3.70	.448	A2 (M = 2.5)	n.s.
B	8.40	.078	B2/B3 (M = 2.125)	n.s
C	11.50	.021	C1 (M = 1.5)	Significant omnibus; no sig. post-hoc
D	2.60	.627	D2 (M = 2.375)	n.s
E	2.50	.645	E1 (M = 2.25)	n.s
F	7.30	.121	F1/F2 (M = 2.25)	n.s
G	21.50	<.001	G1 (M = 1.5)	Significant omnibus; no sig. post-hoc
H	15.50	.004	H2 (M = 1.75)	Significant omnibus; no sig. post-hoc
I	26.30	<.001	I1 (M = 1.125)	Significant omnibus; no sig. post-hoc
J	4.90	.298	J1 (M = 2.125)	n.s

Table 6: Summary of Friedman tests and descriptive top-ranked interactions across all props (A–J) on the *Ease of Use* measures. Mean rank: lower is better (1 = best, 5 = worst). "n.s." = not significant. For props with significant omnibus effects (C, F–J), no Wilcoxon pairwise comparisons survived Holm correction.