Exploring the Role of Mixed Reality on Design Representations to Enhance User-Involved Co-Design Communication

ANONYMOUS AUTHOR(S)

As users transition from passive subjects to active partners in the co-design process, they bring unique insights based on their experiences, collaboratively envisioning a better future with designers. However, unlike designers who are adept at various forms of representation, most users lack advanced modeling or sketching skills to concretely present the three-dimensional (3D) forms or dynamic features of a design proposal. This hinders user expression and increases the cognitive load on designers, thereby reducing communication efficiency in the co-design process. Mixed Reality (MR) technology enables users to depict 3D information in real physical space using natural gestures. This means that MR can provide a low-learning-cost concrete expression method without compromising traditional communication methods. This study explores the role of Mixed Reality (MR) in enhancing communication between designers and users during the early stages of design. A formative study was conducted to identify four key requirements, which informed the development of the DuoMR system. DuoMR supports designers and users in expressing design ideas through gesture modeling in a collaborative MR space. Results from the user study and practical case study show that DuoMR effectively reduces cognitive load and enhances mutual understanding during the co-design process.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; **Collaborative interaction**.

Additional Key Words and Phrases: Co-Design, User-Designer Communication, Design Representations

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1 INTRODUCTION

User-involved co-design fosters products that meet genuine needs, enhancing their application prospects [60, 73]. While some studies argue that end-users creativity dilute design [23, 24], an increasing consensus supports end-users as active co-design participants [59, 64], especially during the early design stage when concepts are still "fuzzy" and require wide exploration of possibilities [65]. However, a significant challenge in early-stage user-involved design lies in establishing effective communication between users and designers, particularly in three-dimensional (3D) product design. End-users without advanced design skills often encounter difficulties in communicating dynamic interaction and complex geometries of 3D products, which can obstruct mutual understanding and hinder the co-design process [36, 40].

Design representation is pivotal in facilitating communication throughout the co-design process. Trained designers can employ various design representations to convey their ideas, including verbal descriptions, gestures, sketches, digital and physical models [13, 54, 57]. Especially, 3D design presentation is widely adopted by designers to identify potential design flaws early, allowing for iterative improvements and ensuring that the final product aligns closely with user expectations [1]. However, when involving users, traditional methods for 3D representation face two primary challenges. First, unlike designers, end-users typically do not have professional spatial perception and lack the necessary skills to understand and imagine 3D product designs [69]. Second, end-users do not have the spatial expression skills that designers acquire through the use of modeling software. They often rely on less precise language and gestures to express their ideas, increasing the miscommunication risk [9, 26, 54]. In the field of human-computer interaction, extensive research has focused on systems and methods that enhance users' abilities to express in three dimensions, primarily aimed at lowering design barriers and enabling independent 3D design [39, 78]. However, the potential of enhanced 3D expression methods to facilitate mutual understanding in co-design remains unexplored.

Mixed Reality (MR) technology has the potential to provide a novel method for 3D representation, allowing individuals to interact directly with virtual 3D objects in real-world settings. This capability significantly enhances communication during the co-design of 3D products by improving both the visualization of concepts and the understanding of interactions [43]. Previous studies have explored the role of MR in co-design contexts, establishing a hybrid space to support prototyping [77], interactive testing [14], and mechanical assembly [76]. These studies demonstrate that MR can seamlessly integrate virtual objects with physical environments, thus enhancing the efficiency of communicating complex 3D information in face-to-face collaborations through intuitive design representation.

Current research has yet to fully investigate the role of MR technology in aiding communication between designers and users during the early stages of 3D product design. This phase is marked by two characteristics: firstly, it requires highly flexible expression to cater to diverse design tasks [65], rather than relying on pre-developed modular components; second, the range of abilities to express 3D information among collaborators varies significantly [45], necessitating consideration of MR system's assistance across diverse groups. Therefore, it becomes essential to conduct research on how MR technology can enhance communication in the preliminary phases of 3D product design. This research should focus on how MR can be utilized to offer opportunities for flexible expression and be adaptable for collaborators with diverse expressive capabilities.

In our study, we initially conducted a formative study to identify communication barriers within user-involved co-design processes for early-stage 3D product development that MR could potentially overcome (Section 3). Based on the findings, we outlined design goals and implemented the first version of the DuoMR (Section 4.1). After a rapid test, we optimized certain features and completed the development of DuoMR (Section 4.2). This system enables designers and users to swiftly express 3D structures and dynamic features of 3D product, set up custom scenarios in a wide field, and perform real-time interaction simulations in a collaborative MR design space. We conducted a user study to assess the system's usability (Section 6), and investigated how DuoMR influences the communication styles and role shifts of designers and users in the co-design process. Finally, we explored the impact of DuoMR in real-world, multi-role design environments through a practical application case (Section 7). The main contributions of this work are as follows:

- We conducted a formative study to identify and summarize specific communication barriers between users and designers during the co-design process.
- We developed DuoMR, an MR-based representation tool designed to enhance communication during co-design. DuoMR enables both users and designers to use gestures to intuitively and quickly express structures, dynamic features, and interactive processes of 3D products.
- We evaluated DuoMR through a user study and a practical case study, analyzing its impact on design process workload, its effectiveness in supporting communication within design teams, and its effects on participant behavior. These insights provide valuable guidance for future research on integrating MR into the co-design process.

2 BACKGROUND AND RELATED WORK

2.1 User-Involved Co-Design

Integrating users into the design process has been extensively explored, particularly through user-centered design, participatory design, and co-design [52, 60, 65, 67]. User-centered design treats users as subjects, gathering insights through observations and interviews [44, 63], while participatory design views them as partners, with designers guiding and co-creating, providing professional insights into design choices [21, 49, 63]. Co-design, emerging from user-centered principles, emphasizes collaboration between designers and non-designers [65]. The definitions of these concepts are somewhat vague; however, all three emphasize the importance of active user participation in design [19, 53, 65]. Our study adopts co-design to emphasize a collaborative approach where users actively participate as partners, especially in smaller-scale projects that focus on early-stage interactions between designers and users, distinct from the larger-scale projects typical of participatory design [60, 65, 67].

The integration of users in the design process offers several advantages. Primarily, it ensures that products are more attuned to user needs [31, 60]. Secondly, involving users as collaborative partners in the design process fosters co-creativity, merging their creative contributions with those of professional designers [74, 81]. Despite the benefits of user-involved co-design, its practical implementation still faces many challenges. An primary obstacle is the lack of a shared medium for effective communication of design concepts between designers and end-users. It provides an intuitive basis for understanding design information, as well as an anchor point for discussing the next design iteration. For this reason, designers often need to take on an additional translation role to help users understand and express design concepts. For instance, Sanders [62] used a 3D toolkit to help patients design hospital rooms, facilitating the communication of concepts.

Existing methods for building shared medium and assisting users in understanding and expressing concept in 3D product design have some inherent limitations. First, the creation of user-specific expression tools for each design task is time-consuming and labor-intensive [65]. Second, modular tools may inadvertently limit users' ability to move beyond existing paradigms and envision innovative futures [20, 73]. Introducing these tools early in the design process can lead to design fixation, thereby constraining innovation and novelty [33, 41, 56]. MR has the potential to overcome existing method limitations by compensating for users' lack of concrete expression skills and allowing unrestricted expression without the need for specialized tools. Therefore, this paper explores how MR technology can enhance creative expression in 3D product co-design.

2.2 Representation in Co-Design

Design representations convey aspects of a design proposal utilizing physical or virtual methods in 2D or 3D media [54]. These representations play a crucial role in visualizing, communicating, and storing information in design [17, 70]. Different representations have unique characteristics and assist in varied levels of expression during communication. For example, verbal discussion helps clarify abstract concepts, while sketches offer a visual reference that captures the structure and appearance of objects. Gestures add dynamism and can express abstract ideas that are challenging to articulate in words or drawings [50]. Physical or digital models facilitate embodied interactions with products in a 3D space [85]. These representations usually do not function in isolation; instead, they synergistically create a shared imaginative space that enhances collaboration within design teams [16, 50].

However, the design representations available for communication support during the early stages of 3D product design are limited. Beyond verbal discussions [42] and gestures [30], design teams primarily rely on sketches [11], mock-ups [32, 35], and preliminary digital models [13] for rapid expression. Specifically, in 2D representations, sketches are quicker to produce than polished images and are more effective at enhancing idea generation [15]. In the realm of physical models, rough models are easier to produce and more suitable for creative ideation than labor-intensive detailed models due to their limited precision [72]. Similarly, in digital models, rough versions are more appropriate for the early design stages [2, 54].

Although these traditional representation methods provide sufficient expressive capabilities for trained designers, they are often inadequate for users. This means that the 3D information expressed by users is often vague and abstract. On one hand, This discrepancy can lead to misunderstandings and increased cognitive load for designers who need to interpret users' ideas [54]. On the other hand, when expression methods are asymmetrical, users need to expend effort to match and correct their understanding of the designer's expressions [12]. Given MR's ability to effectively visualize 3D structures, this study explores its potential to lessen the cognitive burden on design team members during communications about 3D product design.

2.3 Mixed Reality for Visualization and Collaboration

Immersive technologies offer novel modalities for 3D information representation [3, 4, 77, 83], holding potential to enhance co-design process by improving participants' expressive capabilities [25, 58]. Specifically, these technologies facilitate natural expression within a 3D environment, overcoming limitations inherent in 2D sketching, such as depicting depth from a single perspective [3, 84]. For example, Surface Drawing allows users in VR environments to construct and adjust models through gestures and physical instruments [66]. Additionally, MR supports direct interaction between virtual objects and real environments or people. For instance, people can add virtual table extensions directly adjacent to a real table to clearly demonstrate their design concepts [80]. Lee et al. [40] designed a system enabling users to complete ergonomic settings via immersive technology, significantly lowering the design threshold. These studies indicate that MR can greatly reduce communication challenges related to dimensions and ergonomics.

Existing research has demonstrated that MR can effectively assist in later stages of design, where the product's general form is established and only detailed refinements are required. For example, MR aids in packaging design by superimposing virtual information onto physical prototypes [8, 25]. Studies also focus on specific design tasks, providing collaborators with 3D representations of design objects to facilitate mutual understanding. Applications include pipeline layout design [76] or surgical procedure explanations [86]. These applications have one thing in common: the predictability of design variables. Designers can develop specific MR tools tailored to these design tasks. In contrast, the early design stage features highly flexible expression with unpredictable variables [65]. This study intends to delve deeper into the influence of MR's free expression capabilities on collaborative communication during the early design phases and explores how MR helps designers and users achieve communication consensus.

3 FORMATIVE STUDY

A formative study was conducted to identify potential communication barriers and requirements in the co-design process involving users. Sixteen participants, divided into eight pairs consisting of one designer and one user, took part in the study. All designers had at least two years of experience in industrial or product design, with four classified as senior designers having over five years of experience.

3.1 Settings and Procedure

To delve deeper into the communication challenges faced by designers and users during the early stages of 3D product design, we defined the experimental task as "designing a smart device for posture correction" for the following reasons: (1) The need for "posture correction" is common, allowing us to recruit participants from diverse professional backgrounds and work environments. This diversity amplifies the complexity for designers in understanding user scenarios, emphasizing the communication difficulties in grasping users' requirements. (2) The need for "posture correction" closely pertains to the human body [40], encouraging discussions about the spatial and interactive relationships between product components and the human body, thereby highlighting communication challenges related to 3D and dynamic information. (3) Participants are tasked with designing a "smart product" to move beyond established frameworks, restricting the use of existing products for analogous expressions and encouraging the conveyance of ideas through visualization, thus highlighting communication challenges due to limited visualization abilities.

Our study simulated a conventional design setting, providing participants with design materials including drafting paper, various pens, as well as a laptop equipped with standard design software (e.g., CAD, Rhino). The experiment lasted one hour, divided into two stages. The first phase, lasting about 40 minutes, required designers and users to collaboratively complete design tasks. The second phase, lasting about 20 minutes, involved one-on-one semi-structured interviews conducted separately with the designer and the user by two experimenters. Aligned with the research goals, we developed separate interview outlines for designers and users to uncover communication barriers, focusing on user expression, designer expression, consensus on requirements, and consensus on solutions (detailed in Appendix A).

3.2 Findings: Requirements on User-Designer Communication During Co-Design

Potential barriers and requirements to communication in the co-design process were summarized and extracted through thematic analysis. During the design task stage, we recorded approximately 300 minutes of video documenting the communicative and interactive dynamics between designers and users. During the interviews stage, we collected about 120,000 words from interview transcripts and conducted a hybrid coding approach [82] for analysis. After a thorough analysis (detailed in Appendix B), four interview codes related to the needs for dual communication during co-design, along with their relevant quotations, were identified (see Table 1).

3D expression (E). Supporting rapid expression of 3D forms is essential. Both designers and users found it challenging to quickly convey the 3D form of a product during communication. Users often resorted to using language or gestures to express their ideas (E1) because they lacked professional design skills such as sketching. Most users (7/8) believed that sketching skills could significantly enhance their ability to express the 3D form of products. Designers also found it challenging to express a product's 3D form in a limited time despite their more advanced sketching skills (E2). Moreover, even though there were no restrictions on using computer software or physical materials, few designers (1/8) chose expression methods other than sketching, believing that modeling or physical prototyping would be too time-consuming.

Dynamic simulation (S). Offering a simple method for dynamic expression enables both designers and users to better convey the dynamic effects of products during communication. Expressing dynamic effects is more challenging than conveying 3D forms. Designers often used basic gestures or arrows on sketches to indicate simple state changes, but these methods were insufficient for fully exhibiting the interaction effect to users (S1). Without sketching skills, users found it difficult to express product dynamics, often resulting in a passive role during the design process where they waited for the designer's solutions before making choices or improvements (S2).

Table 1. The Codes and part of the quotes for the requirements. The note 'D' represents designer while 'U' represents user.

Requirements	Codes	Part of the quotes
3D expression (**E**)	**E1**: User's limited sketching skills	U7: "*The sketch I drew did not have a 3D structure, and the designer seemed to grasp roughly 60% of it.*" U3: "*If I had the ability to sketch, my expression of structures would be faster, as I already have a rough idea in my mind.*"
	E2: Time limit	D1: "*In fact, the U-shaped component was quite simple, but drawing it with perspective was more challenging; given the time constraints, I may not have handled the perspective lines well.*" U3: "*At the time, I did not fully understand the diagram drawn by the designer; I could comprehend about two-thirds of it.*"
Dynamic simulation (**S**)	**S1**: Designers' rough expression	D2: "*There is relatively little dynamic expression regarding how the shawl conforms to the human body.*" U3: "*In the instance where the designer illustrated the storage of the cushion via sketches, I actually only understood the cushion part.*"
	S2: Users' passivity	D1: "*In cases where users have no ideas of their own, they can only choose from the sketches presented by the designer.*" D2: "*The designer is responsible for addressing the gaps left by users' unexpressed needs. The outcomes derived solely from the designer's speculation may not always fulfill the users' needs.*"
Customized usage scene (**C**)	**C1**: User's ignoration of needs	D1: "*I inquired if he had issues with crossing his legs, to which he affirmed, noting that he had initially forgotten about it.*" U5: "*The designer had alerted me to the issue regarding leg posture at the time, which I indeed had not considered.*"
	C2: Designers' empathy gap	D3: "*His requirements did not align with my experience, as I normally do not sleep in chairs.*" D5: "*The requirements he proposed exceeded my expectations.*"
Interaction exhibition (**I**)	**I1**: User's vague understanding	U1: "*I was uncertain about how to adjust the parameters, which parameters to modify, and the function of the reminder system.*" U6: "*Numerous details remained unclear to me, such as the size, texture and position of the magnetic snaps.*"
	I2: User's elevated cognitive load	"*Initially, my intention was to move the chair forward*", U4 explained how he planned to address the issue of a forward-leaning sitting posture, "*But later I realized that the forward lean was actually due to the chair's height, so adjusting its height would alleviate the issue of distance.*"
	I3: Designers' uncertainty on user understanding	D2: "*I believe that if the user expresses agreement while concurrently lowering their voice, this could signify some compromise.*" D5: "*I am uncertain whether he understood my final proposal, given that his imagination of certain aspects might differ from mine.*"

Customized usage scene (C). Recreating users' life scenarios in the design space served two purposes. First, it enabled designers to uncover needs that users might have overlooked through observation, allowing designers to better empathize with users' pain points. It is impractical for designers to visit users' actual living spaces to obtain the most authentic observational conditions due to time and energy costs, and privacy concerns. Away from their living scenarios, users relied on memory to describe their experiences, inevitably leading to overlooked needs (C1). Additionally, designers who lacked similar life experiences as the users struggled to grasp users' pain points (C2). Understanding users in their usage scenarios can enhance designers' empathy towards these pain points.

Interaction exhibition (I). Displaying product interactions in real 3D scenes ensured that designers could verify users' comprehension of these interactions. Our experiments revealed that users' understanding of the interaction process was vague (I1). This ambiguity increased users' cognitive load in understanding, imagination, and confirmation (I2). Consequently, it raised their communication costs and led to uncertainty in designers' understanding of users (I3).

Directly presenting the design of product interactions visualized vague concepts, allowing users and designers to quickly reach a consensus with the confidence that their understanding was aligned.

3.3 Design Goals

Based on the findings from the formative study, HoloLens was selected as the MR device for the following reasons: (1) HoloLens supports hands-free control through gesture-based interactions, maximizing mobility during communication; (2) HoloLens offers a broader view than tablets, enabling complete observation of product spatial interactions. Considering the four identified requirements and the capabilities of the HoloLens, we established four design goals to improve designer-user communication.

- **G1: Allowing swift 3D expression (E).** This approach should simplify 3D representation, thereby enhancing the ability of both designers and users to quickly articulate 3D models.
- **G2: Providing intuitive expression for dynamic features (S).** The MR system should offer an intuitive dynamic display method based on simple gestures, thereby enhancing the ability of both designers and users to articulate dynamic aspects of products.
- **G3: Enabling the creation of custom usage scenes within a broad view (C).** Users and designers should be able to create usage scenes of products, allowing users to clearly describe their real-life scenarios and designers to better explain how to use the designed products. The wide field of view of HoloLens enables collaborators to create realistic, life-sized scenes. The system should provide controls for adjusting scenes at different distances, allowing versatile manipulation.
- **G4: Facilitating real-time interactive exhibitions under a synchronized view (I).** The system should support vision synchronization among collaborators, enabling members to view each other's content in real time. This ensures that virtual information maintains consistent appearance and spatial positioning for all parties. Such synchronization allows designers to more effectively demonstrate the product's interactive pathways, thereby enhancing users' understanding of interaction effects.

4 SYSTEM DESIGN AND ITERATION

4.1 System Iteration #1

We proposed DuoMR 1.0 to fulfill design goals basically. Here, DuoMR was named to highlight the bidirectional communication and mutual understanding between users and designers in the MR space.

4.1.1 Main Functions for DuoMR 1.0. The core function of DuoMR 1.0 is mid-air sketching. Designers and users can draw lines in 3D space with a simple pinching gesture, expressing the product's spatial position and form, reducing the need for perspective transformation in traditional sketching. They can also modify the width and color of their strokes. Subsequently, designers and users can easily create 3D representations by sketching in mid-air (**G1**) and use elements like colored arrows to indicate dynamic aspects of the product (**G2**). Furthermore, utilizing the HoloLens' extensive field of view, users can depict comprehensive usage scenarios (**G3**) and examine the positional relationships between users and the product (**G4**).

4.1.2 Testing and Findings. We conducted rapid testing with two pairs of participants (each consisting of a designer and a user) to evaluate the effectiveness of DuoMR 1.0. During the tests, each pair was given a specific design task. We recorded their system usage and noted the challenges they encountered. Following the test, we conducted separate interviews with designers and users to collect their subjective assessments of the system's usability and to evaluate whether the system effectively achieved our design goals. Based on the participants' feedback, three key shortcomings of DuoMR 1.0 were identified, leading to the proposal of corresponding design improvement plans. In the following sections, 'D' indicates Designer while 'U' indicates User.

- Challenges of mid-air sketching. Participants all expressed difficulty with mid-air sketching. D1 mentioned, *"Drawing in 3D space makes it hard to ensure lines are on a single plane."* U2 also indicated that, *"It's actually hard to discern the 3D structure from pure lines."*
  Design Change #1: From mid-air sketch to mid-air modeling, allowing users to rapidly create 3D models based on gestures.
- Inadequacy in expressing dynamic features. We found that although mid-air sketching enhanced the expression by depicting the dynamic effects of the initial and final states, participants still needed to use gestures to further elucidate the object's movement trajectory and simulate dynamic interactions.
  Design Change #2: Adding flexible transformation tools to facilitate designers and users in more effectively demonstrating the dynamic features of products.
- Lack of auxiliary functions. All participants indicated a desire for more auxiliary functions in the system. D1 said, *"Currently, it's difficult to modify or erase lines; I can only redraw in an empty space, which is quite cumbersome."* U1 added, *"It would be better to have some functions for clearing or adjusting."*
  Design Change #3: Adding auxiliary functions such as delete, transform, and restore to enhance user experience.

4.2 System Iteration #2

Based on the test results of DuoMR 1.0, we identified the core functionalities for DuoMR 2.0, corresponding to the design goals. Through a basic example of designing an intelligent workstation (see Figure 1), we outlined the four key functions of DuoMR 2.0 and their impacts on enhancing co-design processes. First, the user collaborates with the designer to create and confirm the shape of the desk based on their needs (**G1**). Next, the designer illustrates two potential dynamic effects of the adjustable tabletop by dragging the model, providing visual references for the user (**G2**). Using the wide-field custom scenario setup, the designer can adjust the footrest's position in real-time based on the user's body and desk location (**G3**). Ultimately, the designer helps the user simulate and experience the product's interactive capabilities (**G4**). Subsequent sections will detail the roles and operations of the four functions that facilitate co-design.

*4.2.1 Swift 3D Expression through Modeling (for **G1**).*

DuoMR supports three modeling commands (revolve, extrude and sweep), allowing freeform creation of 3D products. This rapid modeling capability helps to express the product's dimensions and shape, especially unconventional ones, as well as its 3D relationships with other objects in the space. Figure 1ⓐ and Figure 1ⓑ show the user utilizes DuoMR to quickly demonstrate his idea of the desk shape and its relative position.

The three modeling commands are an extension of the mid-air sketch feature from the first-generation system. The system now auto-aligns lines to a plane, simplifying line control in 3D space. Leveraging the capabilities of mid-air sketching, we developed comprehensive gesture-based modeling methods for each type of modeling command. Figure 2 illustrates the operations of these three modeling commands using the creation of a sweeping machine as an example.

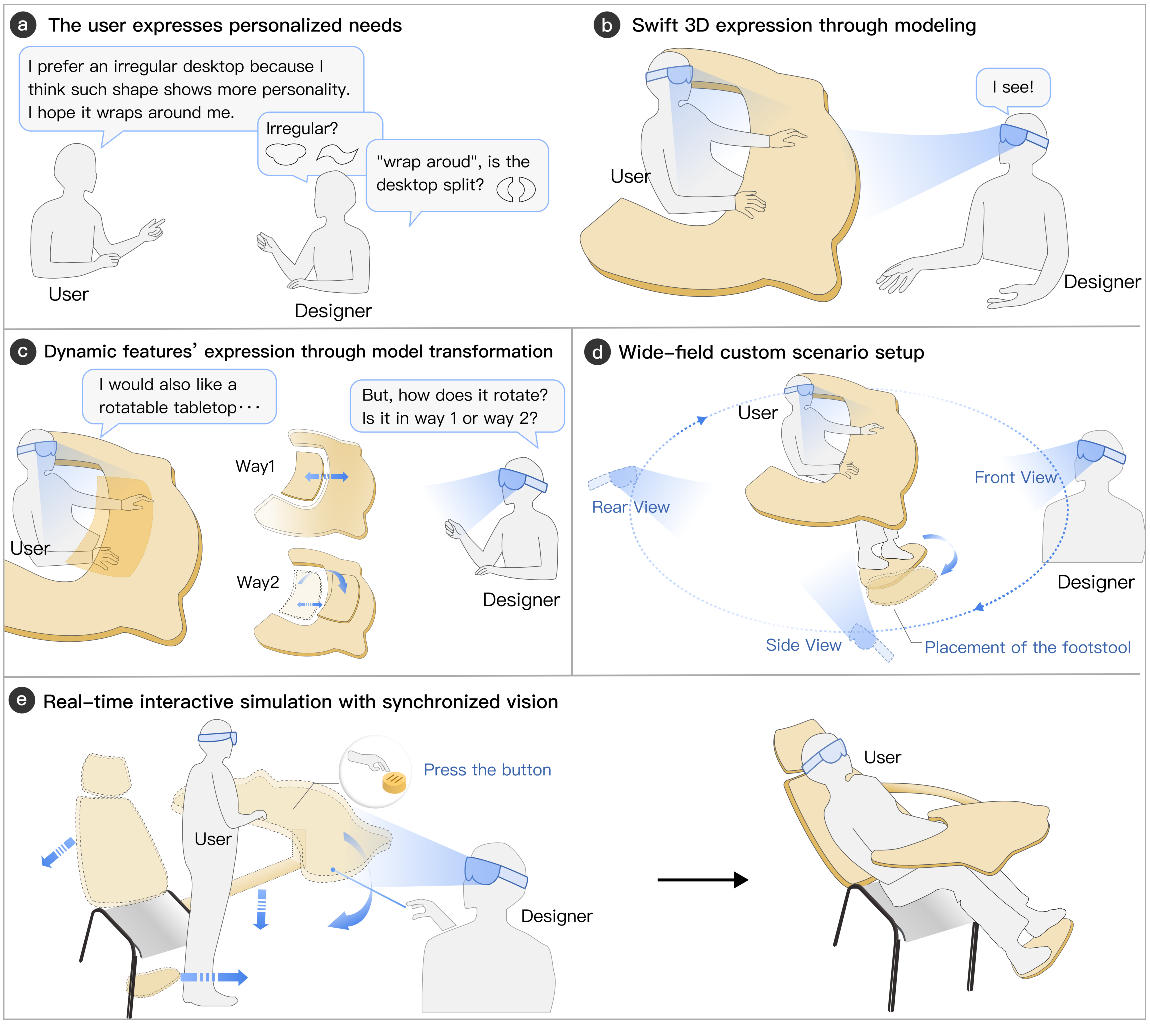

Fig. 1. An example workflow of DuoMR. ⓐ: the user tries to express their requirements for an irregular tabletop; ⓑ: the user creates their desired tabletop shape with DuoMR; ⓒ: The designer utilizes DuoMR to showcase two usage options for the tabletop to the user; ⓓ: the designer adjusts the footrest position with a wide view; ⓔ: the designer collaborates with the user to simulate the complete interactive effect of the product.

- **Revolve**: This command forms a 3D object by revolving a 2D sketch around a predetermined axis. Initially, a vertical axis materializes at the location upon a "*Tap*." A shape is then drawn alongside this axis using a fingertip drag. Once the sketch is complete, a "*Release*" gesture triggers the "*Revolve*" command, materializing the model at the sketched location.
- **Extrude**: This command generates a 3D object with defined depth or thickness by extruding a 2D sketch in a specified direction. Initially, a "*Tap*" gesture creates the model's cross-sectional shape in mid-air. Upon executing the "*Release*" command, the system automatically completes the cross-section. Concurrently, the cross-section

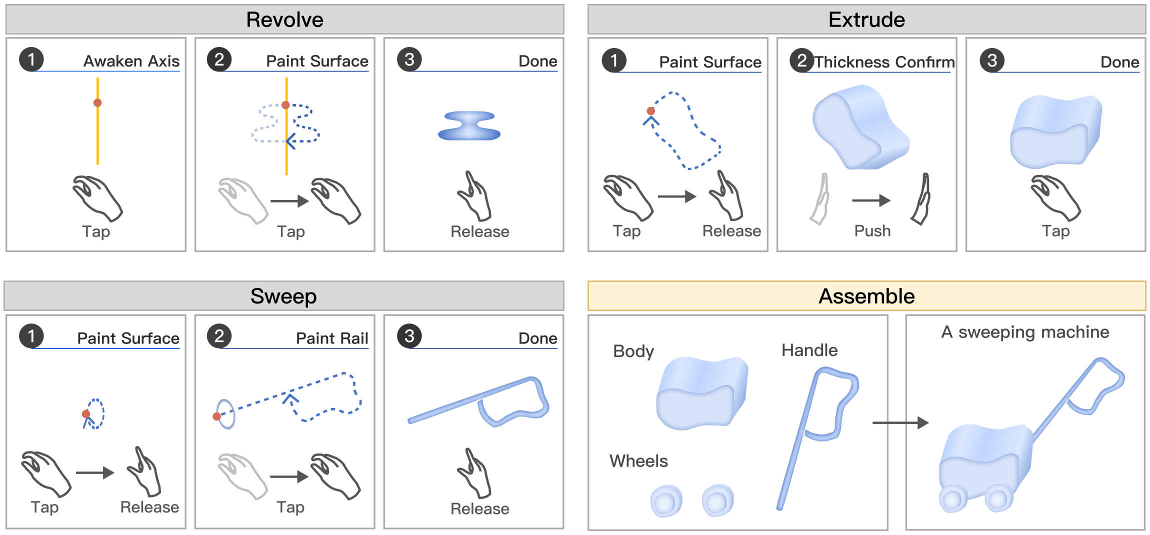

Fig. 2. DuoMR supports three gesture-based modeling commands: revolve, extrude, and sweep. These commands allow designers and users to quickly construct various shapes and then assemble them to form a complete product model.

can be propelled forward using a palm motion, enabling the system to display the model's extrusion effect in real time. The final model is confirmed through a subsequent "*Tap*" gesture.

- **Sweep**: This command generates complex 3D geometries by extruding a 2D sketch along a predefined path. Initially, a cross-section of the model is sketched, followed by delineation of the path from a point on this section. Upon activating the "*Release*" command, the model automatically materializes, stretched along the designated path from the sketched location.

4.2.2 *Dynamic Features' Expression through Model Transformation (for **G2**).*

Following model creation, DuoMR enables collaborators to convey and discuss dynamic features via model transformations, such as product dynamics in terms of form, direction, and extent. Figure 1ⓒ illustrates a detailed example of discussing dynamic information. DuoMR enables designers to demonstrate the desk's dynamic effects by adjusting the positions of various components, allowing users to quickly grasp the dynamic forms. Additionally, DuoMR supports detailed dynamic discussions about the direction and angle of rotation, eliminating the need for complex gestures and verbal descriptions.

4.2.3 *Wide-Field Custom Scenario Setup (for **G3**).*

By combining modeling and transformation functions, collaborators can freely create and simulate product usage scenarios. As illustrated in Figure 1ⓓ, the designer adjusts the footrest's position based on the scene and the user's location. With a wide field of view, the designer can fully observe the user's interactions with the desk and adjust component positions to meet the user's needs. This capability also helps the designer better understand the user's requirements. For instance, the user can recreate and simulate their real-life scenario with virtual objects, allowing the designer to immerse themselves in the recreated environment.

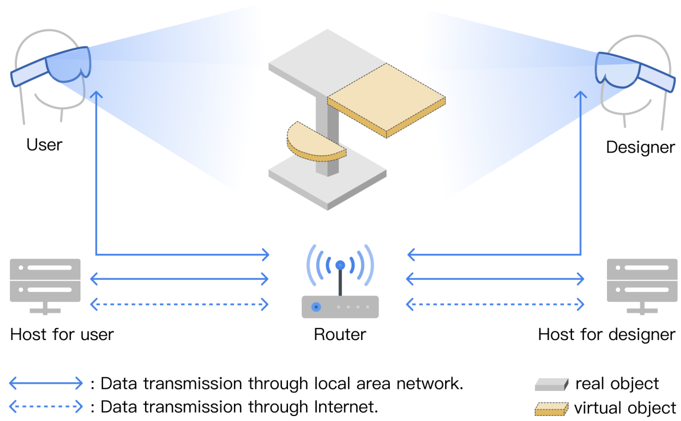

Fig. 3. An illustration of DuoMR's hardware setup and the data transmission. Solid arrows indicate communication between devices for individuals, while dashed arrows denote data synchronization between two persons.

*4.2.4 Real-Time Interaction Simulations in Synchronized View (for **G4**).* DuoMR enables collaborators to employ model transformation techniques to simulate interactions with the product. This method improves users' comprehension of the product interaction mechanism, thus ensuring a shared understanding between users and designers. Additionally, these experiences encourage users to suggest further refinements. Figure 1ⓔ illustrates a case of interaction simulation. After the user mimics pressing a button, the designer controls the movement of the desk, chair, and other components to simulate the interaction effect when the user sits down.

5 SYSTEM IMPLEMENTATION

Figure 3 shows the DuoMR's hardware layout, which includes two Unity-compatible computers, two HoloLens devices, and a router. During co-design, participants wear HoloLens devices linked to individual computers through a local area network for real-time data sharing. In addition, data between the computers is synchronized via the Internet, allowing online plug-in tools to maintain uniform visual perspectives between users and designers.

5.1 Method of Modeling, Editing, and Simulation

Our software development began by setting up a specialized environment for HoloLens applications using Unity (version 2020.3.36) [71] and MRTK (version 2.8) [55]. To facilitate real-time modeling, we integrated two Rhino packages, rhino3dm [47] and compute-rhino3d [46], with Unity. This setup supports the immediate transformation of HoloLens sketches into 3D models via local Rhino servers, with the resulting models rapidly visualized on the HoloLens.

Figure 4 demonstrates the modeling process in the system, using the Revolve modeling command as an example. Firstly, fingertip coordinates are captured through MRTK's gesture recognition during a tap gesture, setting the symmetry axis and drawing path. Once the fingertips are released, the coordinates are reformatted for Rhino to generate the model. The model in 3dm format is not directly usable in Unity; hence, it is converted to a mesh using vertices, triangles, and normals, with materials added to render it visible in Unity.

To enhance model adjustment and editing, the system calculates the model's edges and adds a BoundingBox from the MRTK package for interaction. An auto-following floating menu is then attached to the front of the BoundingBox

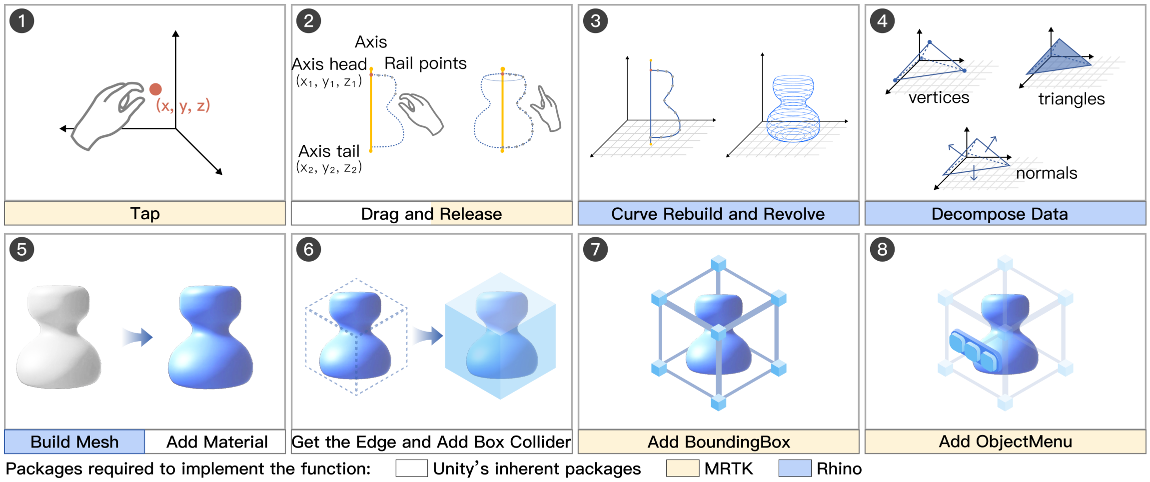

Fig. 4. The implementation of modeling. The color blocks below to each step signify the category of package employed in that specific step. These include: Unity - all packages inherent to Unity; MRTK - all packages from the MRTK toolkit and its expandable packages; Rhino - rhino3dm and compute-rhino3d.

for model control. The BoundingBox can detect hand entry and respond to gestures, instantly adjusting its position, rotation, and scale based on hand movements.

5.2 Method of Synchronizing Vision Between the User and Designer

A major challenge in developing DuoMR is maintaining a synchronized visual field across collaborators. In MR environments, unlike 2D platforms, virtual objects often align in the same real-world coordinates across different perspectives. A significant issue occurs when two HoloLens devices are used simultaneously, as each sets up its own spatial coordinate system, causing discrepancies in how the same physical space is represented.

To solve this issue, Photon (PUN) [22] and Azure Spatial Anchor (ASA) [6] services are employed. In this setup, when a HoloLens is activated, it scans the surrounding environment. When one member's HoloLens is turned on first, it immediately establishes a spatial anchor and logs its position using ASA. Subsequently, the other member's HoloLens accesses this anchor via PUN to sync coordinates based on its environmental scan. This procedure guarantees that operations within the system are coordinated by the anchor, with relevant data shared through PUN. Thus, virtual data positioning remains consistent across both HoloLens devices, providing a synchronized visual experience.

6 USER STUDY

We executed a controlled experiment to assess the effectiveness of the proposed DuoMR system in facilitating communication between designers and users during the co-design process. Figure 5 illustrates the experimental environment and procedures.

6.1 Participants

In our experiment, 48 participants were involved: 24 with a design-related background assuming the designer role and the remaining 24 without a design background assuming the user role. The experimental group (MR group) and

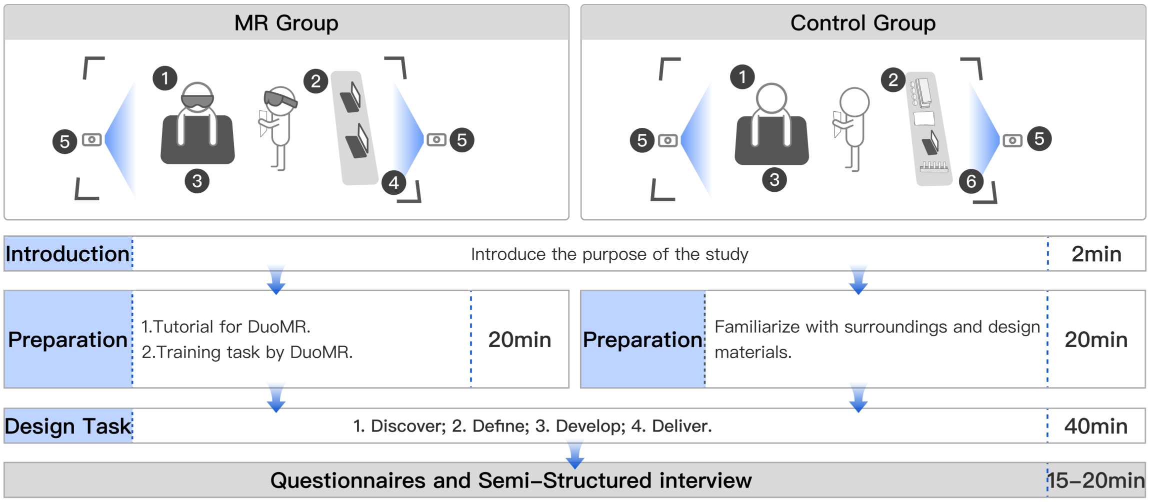

Fig. 5. The experimental setting and procedures of the user study. The area labeled ① refers to the participating user, ② to the participating designer; ③ to the design reference for the design task (a height-adjustable table); ④ to the local server for DuoMR; ⑤ to the recording camera; ⑥ to the design materials for design task.

control group included 12 designers and 12 users each. Designers (9 male and 15 female, aged 20 to 30) were all from fields related to design, with experience ranging from 1 to 10 years ($M = 4.33$, $SD = 2.22$). For the MR group, the demographic survey included a question about their familiarity with HoloLens. The assessments were carried out using a 1-7 Likert scale (1 = totally unfamiliar, and 7 = expertly familiar). The results showed that the designers had limited familiarity with HoloLens ($M = 2.58$, $SD = 1.16$). Participants (12 male and 12 female, aged 20 to 30) who had a need for standing desks were recruited as users. Users in the MR group also filled out a questionnaire on their knowledge of modeling software and HoloLens, and the results showed that they had limited familiarity with both (Modeling: $M = 2.41$, $SD = 0.29$; HoloLens: $M = 1.08$, $SD = 0.29$).

6.2 Environmental Setting

The upper half of Figure 5 illustrates our experimental setting. Both the experimental and control groups conducted their experiments at the same location. Two cameras, positioned at the front and rear, and a centrally placed microphone recorded the entire procedure. The two groups used different materials and tools to complete design tasks, except for paper and pens, which were provided to both groups.

The MR group used HoloLens running DuoMR for communication. The recording features of the two HoloLens devices were activated to record the design process from a first-person perspective. The control group employed computers and additional physical materials provided. Especially, the computers equipped with common design software like CAD and Rhino. Physical materials and tools included mark pen, cutter, scissors, masking tape, glue, paper, whiteboard, sticky notes, boxboard, foam, modelling clay and sticks.

6.3 Procedure and Design Task

The lower half of Figure 5 illustrates our experimental procedures. At the beginning of the experiment, researchers introduced the study aim and experiment task to participants. Participants then familiarized with the experimental

Table 2. The questionnaires used in the user study.

Evaluation Content	Questions / Questionnaire
System usability	System Usability Scale [10]
Design process workload	NASA TLX [28]
General communication satisfaction	Interpersonal Communication Satisfaction Inventory [29]
User-designer communication consensus	**For user:** 1. I believe the designer understands my needs. 2. I understand the designer's proposal. **For designer:** 1. I understand the user's needs. 2. I believe that the user understands my design proposal.

environment and design materials. For the control group, participants needed to familiar with design software and physical materials provided. For the MR group, participants were required to learn operations of DuoMR. We used different training tasks to demonstrate the different functions of DuoMR. For instance, a task involved modeling a desktop extension, where participants created an extension panel and positioned it next to a real desk to recognize the interactive potential between virtual models and the real world.

After familiarization, designers and users in each group collaborate to complete a design task based on the Double Diamond framework [61]. It involved creating a smart standing desk through four 10-minute stages: Discover, Define, Develop, and Deliver. In the Discover phrase, users conveyed their requirements, while designers employed observation and questioning to identify needs. In the Define phase, participants were expected to complete the core functionalities of the product and establish basic interaction paths. During the Develop phrase, participants used their respective tools to further detail the product's design. Finally, during the Deliver phase, users were encouraged to submit further requirements based on their prototype experience, and designers were to refine the final design accordingly. Participants had access to all materials and tools throughout these stages. After completing the design task, participants filled out questionnaires and participated in semi-structured interviews.

6.4 Questionnaire and Semi-structured Interview

Four questionnaires (see Table 2) were utilized to evaluate participants' perceptions on system usability, design process workload, general communication satisfaction, and user-designer communication consensus. Specifically, System Usability Scale (SUS) [10] was used to evaluate the usability of the DuoMR system. The NASA Task Load Index (TLX) [28] was adopted to assess the workload of the collaborative design process. To measure general communication satisfaction, we adopted Hecht's interpersonal communication satisfaction inventory (16-item version) [29]. To assess the consensus in communication between users and designers, we formulated two tailor-made questions focused on understanding requirements and design proposals. Responses were measured using a seven-point Likert scale. The completion of questionnaires took between 15 to 20 minutes.

After completing the questionnaires, we conducted one-on-one semi-structured interviews with the participants. The interview content was aligned with the findings of the formative study, concentrating on whether the developed DuoMR system achieved our design goals. Key discussion topics included the expression and comprehension of: (1) user's needs, (2) the product's 3D forms and dynamic features, (3) interactive paths and effects of the product, and (4) a mutual consensus on the final design.

6.5 Results: DuoMR's Usability

The overall average SUS score of DuoMR was 71.82, with designers averaging 72.95 and users averaging 70.68. According to SUS standards [7], the overall score falls in the "Good" range, indicating generally positive usability. Designers rated the system slightly higher than users, suggesting it aligns better with their workflows. The main factor influencing participants' ratings of the system's usability was the accuracy of gesture recognition during communication, which was limited by the capabilities of HoloLens. This problem might be resolved by using more advanced MR equipment, such as the Apple Vision Pro. In the following sections, we use 'CG' to refer to the control group and 'MR' for the MR group. Additionally, we use 'D' to represent Designers and 'U' for Users.

6.6 Results: Collaborative Design Process Workload Assessment

To evaluate the impact of MR technology on the co-design process, our study employed the NASA TLX. We utilized the Mann-Whitney U Test [51] to analyze results, a non-parametric statistical test chosen for its appropriateness in comparing independent samples with non-normally distributed data. The results are shown in Figure 6.

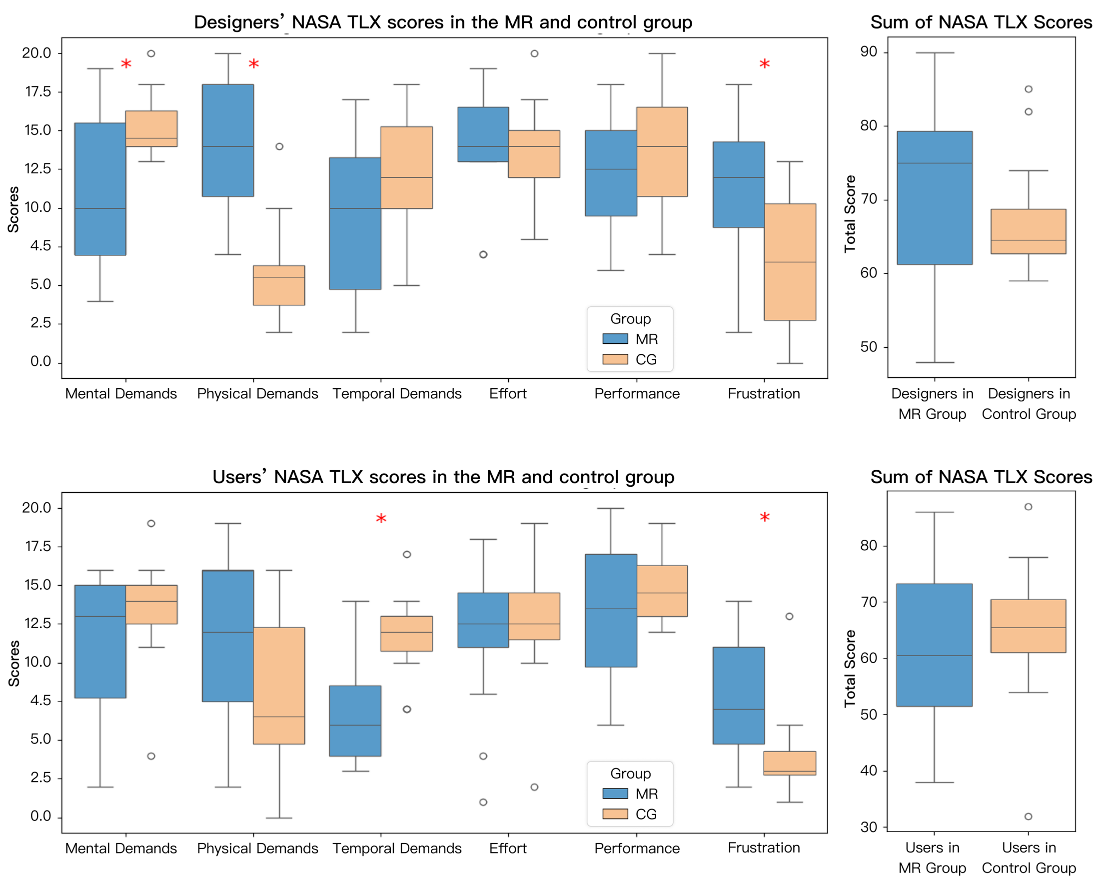

Fig. 6. The NASA TLX scores in the MR and control group. * indicates a significant difference.

6.6.1 Quantitative Results. The results revealed that DuoMR overall enhanced the collaborative experience. For designers, DuoMR led to a notable reduction in mental demands ($U - statistic = 36.5$, $p = 0.042$), underscoring MR's ability to facilitate a more intuitive and less cognitively taxing environment. Similarly, users in the DuoMR setting experienced lower temporal demands ($U - statistic = 20.5$, $p = 0.0031$), reflecting MR's effectiveness in streamlining the design discussion process.

Conversely, the control group fared better in certain aspects, particularly in physical demands for designers ($U - statistic = 135.0$, $p = 0.0003$) and frustration levels for both designers ($U - statistic = 112.0$, $p = 0.022$) and users ($U - statistic = 109.0$, $p = 0.034$). These results align with existing literature suggesting ergonomic challenges in MR environments [18] and the beta nature of our system, which may have led to technical glitches, contributing to user frustrations. These insights highlight areas for improvement in MR technology, emphasizing the need for ergonomic refinement and system stability. While MR offers clear cognitive and efficiency benefits by reducing mental and temporal demands, physical comfort and system maturity remain critical areas for future development.

6.6.2 Qualitative Results. Based on interview results, both designers and users agreed that DuoMR enhances expression clarity, reduces the time needed for designers to verify user ideas, and minimizes misunderstandings between them.

DuoMR reduces the burden on designers' interpretation. Designers in the control group needed to assist users in expressing their ideas. Users conveyed ambiguous ideas through talk and gestures, requiring designers to clarify these concepts through sketches, which often involved multiple rounds of questioning and revising. Among the 12 control groups, participants from 10 groups reported communication difficulties caused by this process of repeated confirmation. CG-U8 said: *"After I expressed the need for a power strip, I had a complete image in mind, but the designer didn't know, so he had to keep asking to clarify."* Conversely, in the MR group, this pattern changed significantly, with users able to present concrete ideas using MR. For example, MR-D6 commented: *"I think this method offers greater advantages to users, their expression has improved noticeably. By creating 3D product models, they can achieve expressions that oral or gestural communication cannot."* This result might explain why designers in the MR group experienced lower mental demands.

DuoMR reduces misunderstandings between collaborators. The ambiguity in expressions within the control group considerably raised the chances of "unrecognized misunderstandings" during communication. Eight control groups reported this issue. As CG-U9 explained: *"I had in mind a curved board, but only after the designer drew it at the final stage did I realize he was thinking of a flat board."* In contrast, the MR groups allowed immediate corrections if a deviation was noticed. As MR-U5 mentioned: *"For instance, as the designer was pulling a part of the product, I could directly tell him to change a bit there, easily finalizing that part."* This could be the primary reason for the reduced time demands on users.

6.7 Results: General Communication Satisfaction

Table 3 shows the questions to evaluate users' and designers' evaluation on general communication satisfaction, and Figure 7 displays the corresponding results. We utilized the 16-item Interpersonal Communication Satisfaction Inventory, structured as a 7-point Likert questionnaire. Among them, six are reverse questions, marked with $^{\#}$. As recommended by Hecht [29], for these six questions, we present the reverse scoring results in Figure 7. This implies that despite the presence of reversed questions in the questionnaire, higher scores continue to signify more positive results.

6.7.1 Quantitative Results. Observations from the designers' side revealed two aspects in which the MR group outperformed the control group. First, designers in the MR group perceived that users provided more effective feedback

Table 3. Questions to evaluate the general communication satisfaction. # indicates reverse-scored questions.

Numbers	Questions
Q1	The other person let me know that I was communicating effectively.
Q2#	Nothing was accomplished.
Q3	I would iike to have another conversation like this one.
Q4	The other person genuinely wanted to get to know me.
Q5#	I was very dissatisfied with the conversation.
Q6	I felt that during the conversation I was able to present myself as I wanted the other person to view me.
Q7	I was very satisfied with the conversation.
Q8	The other person expressed a lot of interest in what I had to say.
Q9#	I did NOT enjoy the conversation.
Q10#	The other person did NOT provide support for what he/she was saying.
Q11	I felt I could talk about anything with the other person.
Q12	We each got to say what we wanted.
Q13	I felt that we could laugh easily together.
Q14	The conversation flowed smoothly.
Q15#	The other person frequently said things which added little to the conversation.
Q16#	We talked about something I was NOT interested in.

during the communication process (Q15) and were able to offer clearer rationales and support for their opinions (Q10). Second, designers in the MR group found the communication process more enjoyable (Q9) and believed they could laugh easily together with their counterparts (Q13). From the users' perspective, we noted that those in the MR group felt that designers showed more interest in their concepts compared to users in the control group (Q8).

However, we also found that users in the control group felt that the communication was more accomplished compared to those in the MR group (Q2). Based on observations, we found that different directions demonstrated in the design process by the two groups. In the MR group, design communication was more oriented towards deeply exploring a limited set of features. Conversely, design in the control group emphasized a broader, horizontal expansion of features (see Section 6.9). As a result, the control group's designs might incorporate a more diverse range of features.

6.7.2 Qualitative Results. Through the concrete expressions of users, MR allowed designers to immersively perceive user needs, thereby enhancing the designers' empathy. This intuitive expression method offered by DuoMR also improved communication speed, enabling both parties to concentrate more on the creative aspects of design and increasing overall enjoyment.

DuoMR boosts designers' empathy of user requirements. Based on observation notes and interview results, we found that users in the MR group could demonstrate their needs and express their design ideas concretely. This significantly enhanced designers' empathy and understanding of user requirements. As MR-D6 stated: *"It felt as if I had set up a stage, and he took center stage to perform."* As a result, users and designers in the MR group gave higher ratings for the clarity of communication and the rationale provided during discussions.

DuoMR enables collaborators to focus more on creativity. In the control group, designers had to infer the specific intentions behind users' words and gestures and verify their guesses through sketches and questioning. CG-D9 said: *"When users expressed themselves using cardboard, I inquired what the cardboard represented and what they*

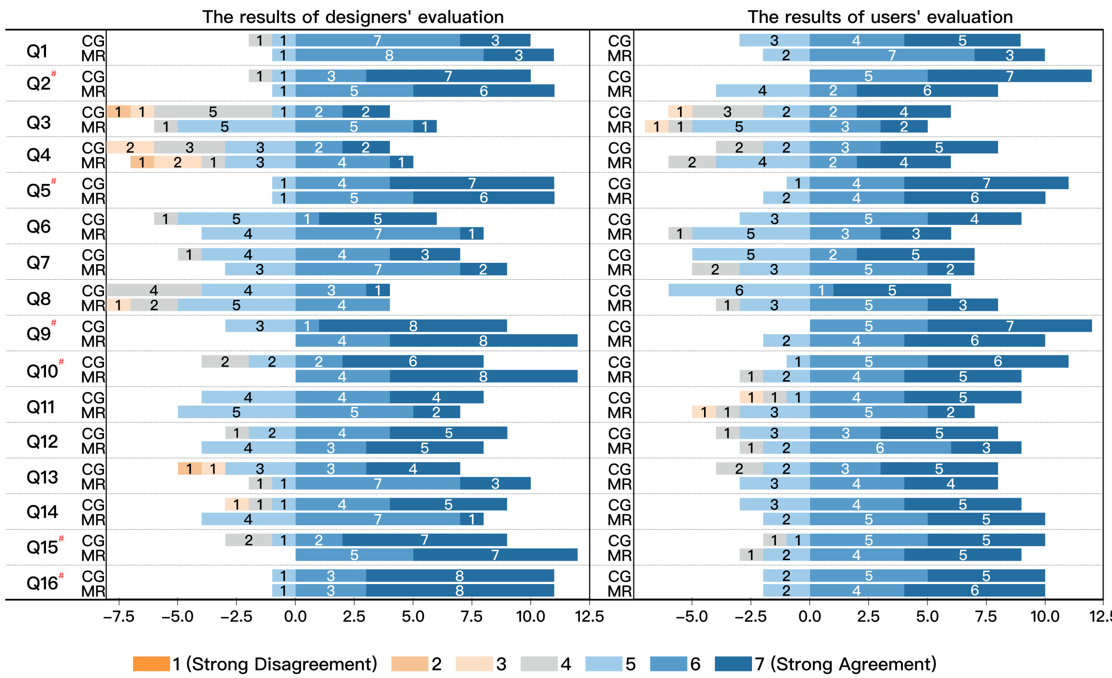

Fig. 7. The results of users' and designers' evaluation on general communication satisfaction. # indicates reversed questions.

intended to convey through it." In contrast, designers in MR groups can redirect more attention from "interpreting users' expressions" to "the convergence of design ideas", thereby encouraging a lively exchange of creative ideas. With the novel interaction mode provided by the DuoMR system, participants in the MR group found the experience more enjoyable and were able to achieve free and immersive creativity [27, 75].

6.8 Results: User-Designer Communication Consensus

We explored the variance in consensus between users and designers on their comprehension of needs and design proposals. Our goal was to examine whether there was a disparity in communication between what one party subjectively believes as "I have understood the other's ideas" and the other's actual feeling of "He/She has understood my ideas." Concentrating on needs and design proposals, we posed relevant questions to both users and designers (see Table 2), allowing us to investigate these discrepancies in consensus through a comparative approach. The Scatterplots was used to visually demonstrate the correlation between users and designers of the two groups. Additionally, we measured the difference in the average distance of the two groups from the line $y = x$ using T-test. Proximity to $y = x$ indicates a greater degree of consensus between designers and users within the group.

6.8.1 Quantitative Results. Regarding the comprehension of needs, the MR group demonstrated greater consensus than the control group ($T = -2.80$, $p = 0.01$). Additionally, from Figure 8, we noticed that the MR group clustered in the upper right corner of the chart, indicating an overall higher understanding of needs than the control group. For the control group, we observed a horizontal distribution of points in the chart. This suggested that even though

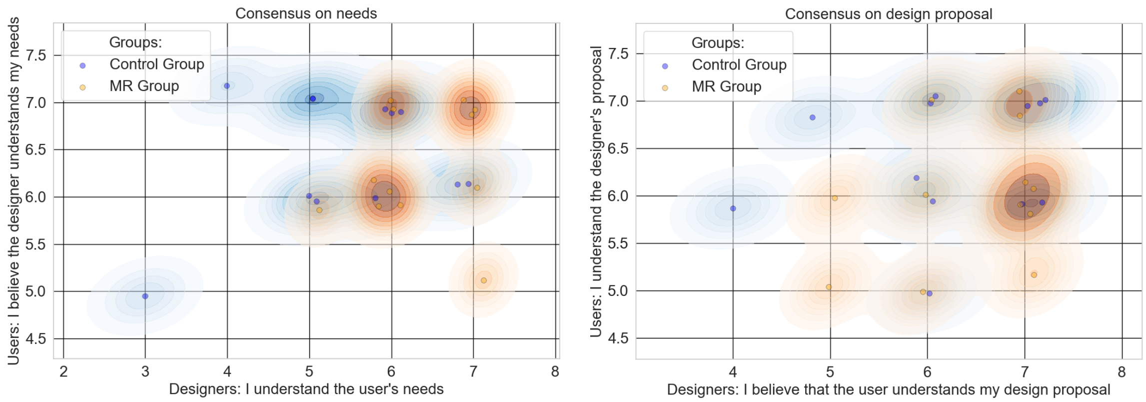

Fig. 8. Consensus between users and designers on needs and design proposals. Left: Consensus on needs; Right: Consensus on design proposals.

designers' assessments of understanding needs varied, users' evaluations were similar. This further substantiated the disparity in expectations within the control group, affirming that DuoMR genuinely augmented the consensus on needs comprehension. The understanding of design proposals did not differ statistically between the two groups, suggesting a similar level of consensus.

6.8.2 Qualitative Results. We interpreted the quantitative results alongside interview findings. Regarding needs, MR group users showed a better understanding of the designers' workflows, resulting in higher consensus. For design proposals, although no statistical difference in consensus were observed between two groups, the MR group had higher overall expectations.

DuoMR enhances users' understanding of designers' workflows. Interviews revealed that the MR group's higher consensus on requirements stemmed from users' better understanding of the designers' workflows. MR-D2 pointed out, *"Unlike with the sketch, they grasped precisely what I was doing and the method involved."* This led users to comprehend the designers' expectations for need collection and redefined what constitutes "good understanding of needs".

Participants in MR group have higher expectations for design proposals. The participants in MR group believed that an effective design dialogue should cover specific aspects of products. For instance, they focused on aspects like the motion trajectory of folding panels in space (MR-D1), the extension distance of mechanical arm (MR-U2), and the size of the foot pedal as well as its position relative to the user's body (MR-U6). Conversely, in the control group, designers and users agreed that a good design dialogue should primarily include the product's general functional form, without the necessity of specifying size, appearance, or detailed dynamics. CG-D2 said: *"Our discussions only led to a consensus on basic functions."* This is not because participants in the control group considered these aspects unimportant, but rather because they felt the materials provided in the experiment were insufficient to discuss these aspects. CG-U6 said: *"Actually, these aspects should be important, like how to control the height of the table and how high it can be raised."* Thus, while there was no significant difference in the quantitative scores for consensus levels on design outputs, this may be attributed to the MR group's higher expectations for design proposals. Interviews suggested that DuoMR expanded the scope of discussions, enabling more comprehensive and in-depth dialogues.

6.9 Results: Behavioral Variation Analysis

Based on behavioral observation notes and interview data from the experiment, we analyzed and summarized three main differences in the behavior of participants in the MR and control groups during design communication.

Differences in depth and scope of design discussion. We observed that during the experiment, the control group included a multitude of features, but delved little into each one. For instance, the third group in the control group designed a modular tabletop, with each section capable of moving horizontally or vertically, including features like a wireless charging area, heating zone, recessed storage space, voice interaction controls, and so on. However, they did not delve deeply into any specific feature, as CG-U3 stated: *"Our discussions mainly revolved around diverging from its functionalities and then piecing them together, without deeply exploring any particular function."* Conversely, the MR group's designs envisioned a relatively smaller number of features, but delved deeper into each one. As an example, the second MR group's design encompassed a foldable tabletop, a rack with telescopic mechanical rods, and an extra vertical monitor. Their in-depth discussions about the mechanical rods covered the position, size, and different ways to control each rod. MR-U2 described the effectiveness of using DuoMR to discuss features, noting: *"I was able to show the whole process, from how it extends upon sensing, the length of extension, to the retraction after detecting an object."*

Variations in the use of verbal discussions and gestures. Another difference was reflected in the way the two groups use representations. Specifically, in the control group, participants combined language and gestures to describe the dynamic content, size, and spatial positioning of items. CG-D1 described their use of gestures: *"I used gestures to explain interaction details beyond what was conveyed in words, like how a tabletop flips."* In the control group, gestures and language were mostly descriptive (CG-D: 10/12, CG-U: 12/12). However, in the MR group, when addressing specific shapes, positions, or dynamic changes, participants used DuoMR for expression. This implied that their use of language or gestures was more deictic. As MR-D11 expressed: *"I don't need to explicitly describe distance or size; I just say 'here,' and the word conveys everything we actually see."*

Additional expressive elements facilitated by DuoMR's support. We observed that the presence of MR allowed participants to discuss new elements, such as the product's complete interaction process and related ergonomics. Despite our explicit request for both groups to establish interaction processes, users in the control group had a vague perception of the interaction. Many expressed uncertainty about interaction details during interviews (CG-U: 11/12), believing that a complete interaction path, including operational methods and product feedback, had never been fully discussed. For example, CG-U3 said: *"We only discussed that pressing a certain button would cause the tabletop to pop up. How exactly to press it, and how the tabletop unfolds, were not addressed."* In the MR group, participants were able to demonstrate the product's interactive effects, enhancing mutual consensus about the interaction (MR-D: 9/12, MR-U: 11/12). Moreover, as this simulation of interaction was conducted in an embodied manner, designers could intuitively observe the interaction effects with the users' bodies, ensuring the product's design was ergonomically sound. For instance, MR-U6 stated, *"When testing the pedal position, I directly measured it using the user's leg to determine the most appropriate placement."*

7 PRACTICAL APPLICATION CASE

To further explore DuoMR's effectiveness in assisting the co-design process in real-world scenarios, we conducted a case study with four participants forming a design team to test the system. We examined how DuoMR influences design discussions involving multiple stakeholders in practical settings.

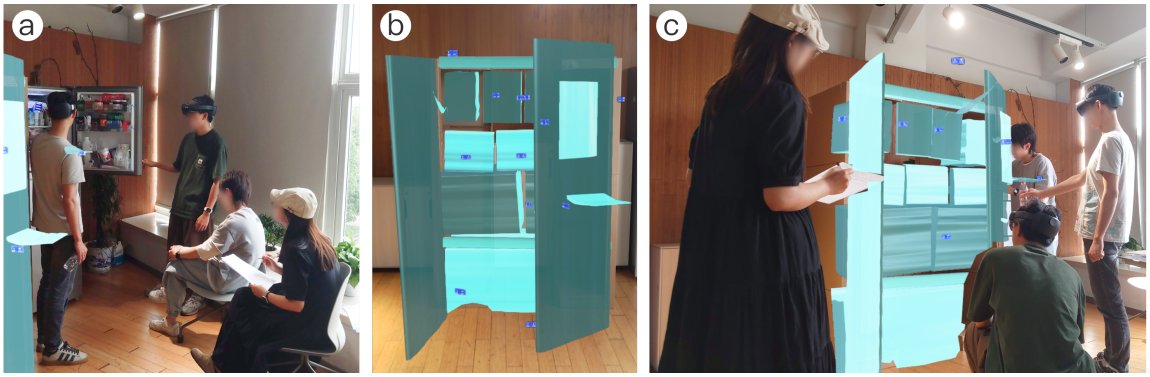

Fig. 9. The illustration of the practical application case. ⓐ: team members observed the actual use of the refrigerator; ⓑ: models were created with DuoMR during the discussion; ⓒ: team members refined and iterated on design ideas based on the created models.

7.1 Research Context

The design team included an industrial designer, an engineering designer, a CMF designer (color, material, and finish), and a user. They were invited to design a refrigerator specifically for the company lounge. Unlike household refrigerators, the one in a company lounge caters to multiple people with varied habits, primarily stores beverages and snacks, and requires a smaller freezer section. Participants engaged in an approximately two-hour open design discussion in the company lounge. Figure 9 illustrates how the team collaboratively used DuoMR to discuss and shape the product's design. After the design session, we conducted a focus group interview with the team to explore their subjective experiences with DuoMR, focusing on its impact on design communication, multi-role collaboration, and potential areas for improvement.

7.2 Interview Findings

In the interviews, we discovered that the parts related to designers and users were consistent with previous findings (see Section 6.5-Section 6.9), but their communication with other roles highlighted new advantages of DuoMR. Specifically, we found that with engineers and CMF designers involved, DuoMR showed potential in demonstrating technical feasibility and color/material selection. In the following section, we use PA-U to refer to the user in the practical application case, PA-D for the industrial designer, PA-E for the engineering designer, and PA-C for the CMF designer.

7.2.1 DuoMR Enables Rapid Assessment of Product Technical Feasibility. In the product design process, specific technologies are linked to particular product parts and require accurate spatial positioning. PA-E illustrated this with the design of the internal camera in a refrigerator: *"After creating the model, I can determine whether the camera would be obstructed in this position, which was quite different from traditional design."* Additionally, engineers are able to perform simple assemblies on-site as needed. During the experiment, when the designer suggested adding an ice maker to the door, the engineer promptly conducted a test: *"For instance, the layout and routing of the water pipes—whether the pipes can be routed from the door to the hinge, etc. The results of these attempts can be immediately applied to make design adjustments."* Consequently, PA-E believed that DuoMR could effectively aid in the initial assessment of technical feasibility and facilitate team consensus on implementing design ideas.

7.2.2 DuoMR Enhances Cross-Disciplinary Knowledge Communication. In design teams, cross-disciplinary discussions involving specialized knowledge are often more challenging than those within the same field. We found that DuoMR could help clarify complex technical information. For example, PA-D noted that engineers can more effectively explain essential structural requirements through MR. In the experiment, while the designer proposed placing the ice maker on the door for user convenience, the engineer challenged its feasibility. PA-D explained, *"He considered the placement of the ice maker and the logistics of water circulation. Through DuoMR, he can better persuade me to revise my ideas."*

3D structural visualization of DuoMR also aided communication between engineers and CMF designers. Engineers can create modules to convey requirements to CMF designers. PA-E remarked, *"For example, some components needed to meet both load-bearing and insulation requirements. The CMF designer's choice of materials also affected my design. Through the system, we can communicate more efficiently."* PA-C added from the perspective of material selection, *"With digital models constructed by modeling software, there might be misunderstandings about the structure. But in MR, you can intuitively see the location, size, and volume of the structure, allowing you to estimate its physical properties and select the appropriate materials."* Therefore, DuoMR's 3D visualization capabilities significantly enhance the efficiency of cross-disciplinary knowledge exchange and comprehension.

8 DISCUSSIONS

8.1 The Distinctions Between DuoMR and Other Design Support Systems

Although DuoMR lets users participate in design similarly to designers, its primary role is to improve communication efficiency between users and designers, rather than reducing the design barrier. Numerous existing approaches aim to lower the design threshold. For instance, Lee et al. [40] introduced a custom furniture design method that enables users to create furniture tailored to their bodies without designer assistance. In contrast, DuoMR emphasizes enhancing the expression and understanding between users and designers, thus increasing user involvement in the design process to better meet their needs. Additionally, existing studies have demonstrated that 3D information [34, 68] and immersive presentations [5, 86] can assist design collaboration, but users often remain passive participants and test subjects [37, 48]. DuoMR allows users to actively engage in the design process, accurately and clearly conveying their design intentions without relying on others to interpret for them (see Section 8.2).

8.2 DuoMR Enhances User Involvement in the Co-design Process

DuoMR empowers users to actively engage in the design process, overcoming three primary limitations of the traditional co-design approach: (1) *Lack of expressive ability.* Traditionally, users rely on designers to articulate their ideas. With DuoMR, users quickly learn to express their design ideas independently in a 3D space, without designer assistance. (2) *Insufficient imaginative capacity.* Users struggle to imagine a complete product from individual features. DuoMR allows them to construct functional components in real space, providing a clear, comprehensive product concept. (3) *Lack of understanding of the design process.* Users are often unclear about the necessary design elements in the process and therefore require guidance from designers. Using the same MR system as designers, users understand the design process better and can give immediate feedback. DuoMR transforms users into co-creators, as MR-D12 stated, *"The users I work with were highly expressive. When we were creating, it's essentially a co-creative atmosphere. Each one of us was creating a part, and then we assemble it together. He hasn't been trained as a designer, yet he was on the same level as me."* Therefore, MR significantly enhance cross-disciplinary knowledge transfer and communication efficiency. This also applies to multi-role design teams (see Section 7.2.2).

8.3 Integrating MR into Traditional Representations

The timing and approach of MR intervention in the design process are critical. Traditional design processes typically evolve from textual descriptions and sketches to low-fidelity prototypes, culminating in high-fidelity prototypes [38]. Early integration of DuoMR can enhance communication efficiency, but it also alters this evolutionary path. For example, members of the MR group immediately experimented with each emerging idea, impacting the divergence and refinement of these ideas. In addition, in the MR group, participants initially preferred traditional oral descriptions for conveying basic concepts during the brainstorming phase. This phase was crucial for broadly exploring requirements and potential solutions, maintaining the expansiveness of the design dialogue. As the design process progressed, MR usage increased. The timing of participants' adoption of MR in the design process reveals its inadequacy in conveying abstract concepts. Consequently, the MR system should be introduced after ample ideation, as the design begins to take a more concrete form. Integration should start gradually, using simple geometric shapes to outline basic ideas, before focusing on the position and form of each component.

8.4 Limitations and Future Work

The primary aim of our study is to enhance user-involved co-design communication through our proposed system. While the system exhibited promising capabilities in enhancing various forms of concrete, dynamic, and experience-based communication, it also exposes limitations needing further exploration.

First, providing features to meet the specific needs of different roles is crucial for enhancing team discussions. Our practical application case study (see Section 7) revealed distinct communication requirements for each team role. For example, the CMF designer suggested that the system should include color selection and material replacement features to better support their design expression. Based on these insights, future research will delve into the diverse needs of design teams and further examine MR's capability to facilitate communication in multi-role scenarios.

Second, improving MR technology application in later design stages can enhance its integration into traditional design processes. Although DuoMR supports early design and prototyping, designers currently rely on photographs for information retention before returning to conventional methods for subsequent stages. However, MR also has the potential to assist in communication during later stages of the design process. For example, adding simple mechanical simulations or animation recording features.

Third, although DuoMR enables effective visualization in design processes, it still demands some time and effort. Additionally, the gesture recognition technology in MR has not yet achieved high precision which has increased frustration. Generative artificial intelligence technology (AI) can generate vivid models and prototypes, significantly reducing both time and effort involved in creation [79]. In our future work, we plan to integrate AI into our system to simplify the creation of 3D models and to accelerate their production.

9 CONCLUSION

This study explores the use of MR as a representational tool to enhance communication in the co-design process involving end-users. Through a formative study, we designed and developed DuoMR which aids design expression and comprehension for users and designers through four core features: (1) swift 3D expression through modeling, (2) dynamic features' expression through model transformation, (3) wide-field custom scenario setup, and (4) real-time interaction simulations in synchronized view. Results from the user study and practical case study indicate that DuoMR effectively reduces cognitive load during communication and enhances mutual understanding.

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A INTERVIEW OUTLINE FOR FORMATIVE STUDY

Table 4. The outlines for interview questions with designers and users in formative study.

Interview key points	**Questions for interviewing Designers**	**Questions for interviewing Users**
User expression	Can you fully understand the user's ideas?	Can you express your ideas clearly?
Designer expression	Can you express your ideas clearly?	Can you fully understand the designer's ideas?
Consensus on requirements	To what extent have you understood the user's requirements?	To what extent do you think the designer has understood your requirements?
Consensus on solutions	To what extent do you think the user has understood the design solutions?	To what extent have you understood the design solutions?

B THE CODING RESULTS FOR THE INTERVIEW OF FORMATIVE STUDY

Table 5. The coding results. 'D' stands for 'Designer' and 'U' denotes 'User'.

Codes	Explanation with quotes
User's limited sketching skills (E1)	Users relied on verbal cues or gestures to communicate. Most users (5/8) acknowledged that incorporating sketching abilities could enhance their communicative efficiency. As U3 noted, *"Proficient drawing skills would make conveying structures more efficient, particularly with a preliminary idea in mind."* A communication gap existed when relying solely on verbal and non-verbal cues, with U7 stated, *"I can convey roughly 80% of my needs, and the remaining portion cannot be conveyed via body language."* Nearly all users (7/8) acknowledged the crucial role of sketching in articulating shapes and structures. For example, U4 stated that *"Words fall short in impact, whereas an image can convey complexities that transcend verbal expression."*
Time limit (E2)	Despite their proficiency in sketching, designers often found it challenging to articulate 3D shapes within limited time. For example, D1, with six years of design experience, noted difficulties in portraying a simple "U shape" in 3D due to time constraints. This issue was exacerbated when collaborating with novice designers. For instance, U3 found it difficult to interpret sketches produced by D3 who had only one year of design experience, and he said *"I find it challenging to comprehend the imagery in the designer's sketches."* Although we provided computers equipped with standard modeling software, only D6 utilized these tools to illustrate the design concepts, and he said to U6 *"I can quickly articulate this concept; please give me a moment."* Conversely, others argued that even the time savings offered by modeling software were insufficient for expedient dialogues, as D1 mentioned *"Even if some objects can be modeled in several minutes, the time required still presents a significant bottleneck in communication."*
Designers' rough expression (S1)	Articulating dynamic product elements posed a complex challenge for designers. To overcome this, they mostly employed gestures , examples or arrows on the sketch. D1 pointed to a certain part of a chair in the experimental scene and explained it to the designer *"I think the chair should arise from here."* Additionally, we observed that the use of sketches to depict dynamic interactions was not effective, as pointed by U3 *"Designers employ sketches to demonstrate how the cushion folds, yet I can only discern the cushion itself."*
Users' passivity (S2)	During our experiment, we observed that although users were active in articulating their requirements, they were largely passive when it came to problem-solving. For instance, D1 emphasized *"The designer takes the lead in the design process. It is my responsibility to present various solutions for users to select."* Users usually found it challenging to generate solutions, and they preferred to choose from options provided by the designers. U5 stated that *"Expressing my needs is easy, but how to achieve them is difficult."* In addition, U7 thought *"Satisfying the demand is essentially the designer's job, not mine."*
User's ignoration of needs (C1)	Users tended to express their requirements based on their lived experiences. For instance, U1 mentioned *"I prioritize comfort because my lunch breaks are short"*. However, the act of extracting needs from memory posed the risk of unintentional omissions, especially when it came to secondary needs. As indicated by the feedback from D1 *"When asking about his daily habits, such as crossing his legs, he confirmed it was a problem but did not initially realize it"*.
Designers' empathy gap (C2)	Designers' comprehension of user needs often hinged on the extent of shared experiences between the two parties. For instance, D4 observed, *"The user's portrayal of the usage context dovetails with my own perspectives."* Conversely, challenges emerged when such commonalities were absent, as articulated by D3 *"The user's requirements diverge from my own experiences; I see no relevance in sleeping in chairs and preferring footstools."*
User's vague understanding (I1)	While users understood the product's essential functions, they were ambiguous about the specifics of interaction. As expressed by U1 *"I'm uncertain about how specific settings are adjusted and how reminders are triggered."* Similarly, U7 expressed uncertainty about the massage feature of the designed chair, *"I know there is a massage function, but I don't understand its operational details."* By further interviewing, we found two main causes of their ambiguity: 1) A lack of awareness, as stated by U5, *"I believed I can manually adjust these settings, so I didn't question the designer."* 2) A belief that some interactions can only be understood through experience, as noted by U7, *"I think the only way to understand these interactions is to use the product, so discussing them in advance is irrelevant."*
User's elevated cognitive load (I2)	A vague understanding of interaction processes could heighten the cognitive costs associated with those functions, leading to unnecessary iterations. For example, when discussing a function to adjust sitting posture with the designer, U4 initially assumed, *"I thought I had to move the chair forward, then adjust the cushion to modify the height."* This initial misunderstanding led him to overlook the full scope of the interaction process. He later realized , *"Actually, the height is primarily affected by the back of the seat, negating the need for front-to-back adjustments."* This realization took him close to 10 minutes during the experiment.
Designer's uncertainty on user understanding (I3)	We observed that most designers were cognizant of the issue that users may only grasp a portion of the design solutions. For example, D1 mentioned, *"Complete understanding would only be possible if the user has used the product I referenced, which is not the case."* Additionally, designers noted the vague feedback from users, with D4 commenting, *"Sometimes the user's approval is ambiguous, and no specific suggestions are provided."* They also expressed concerns about the users' comprehension of the entire design solution. D5 said, *"I'm uncertain if he fully understood my final plan, as some interactions may have confused him."*