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

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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 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 dilutes 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]. In particular, 3D design representations are 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 lack professional spatial perception and the necessary skills to understand and imagine 3D product designs [69]. Second, end-users usually 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 risk of miscommunication [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 directly interact 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 improving 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; Secondly, the range of abilities to express 3D information among collaborators varies significantly [45], necessitating consideration of how MR systems can assist 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 in early-stage user-involved co-design of 3D products that MR could potentially overcome (Section 3).

Based on the findings, we outlined design goals and implemented the first version of DuoMR (Section 4.1). After rapid testing, we optimized certain features (Section 4.2) and completed the development of DuoMR (Section 5). This system enables designers and users to swiftly express 3D structures and dynamic features of 3D products, 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 the design process workload, effectiveness in supporting communication within design teams, and 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]. Participatory design views users as partners, with designers guiding and co-creating while 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. This is especially relevant 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. A primary obstacle is the lack of a shared medium for effective communication of design concepts between designers and end-users. Such a medium 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 role of translator 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 a shared medium and assisting users in understanding and expressing concepts 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 the limitations of existing methods 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 with expression at various levels during communication. For example, verbal discussions help 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 in 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 because of 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 the co-design process by improving participants' expressive capabilities [25, 58]. Specifically, these technologies facilitate natural expression within a 3D environment, overcoming the 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, real environments, and 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 has been established and only detailed refinements remain. 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] and 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 aims to delve deeper into the influence of MR's free expression capabilities on collaborative communication during the early design phases and to explore how MR helps designers and users achieve communication consensus.

3 Formative Study

We conducted a formative study to identify potential communication barriers and requirements in the user-involved co-design process. Sixteen participants took part in the study. They were divided into eight pairs, each consisting of one designer and one user. 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, limiting 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, and 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 each designer and 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 communication barriers and requirements 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

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.*"
	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.*"
Dynamic simulation (**S**)	**S1**: Designers' rough expression	D2: "*There is relatively little dynamic expression regarding how the shawl conforms to the human body.*"
	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.*"
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.*"
	C2: Designers' empathy gap	D3: "*His requirements did not align with my experience, as I normally do not sleep in chairs.*"
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.*"
	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.*"

and users. During the interviews stage, we collected about 120,000 words from interview transcripts and analyzed them using a hybrid coding approach [82]. After a thorough analysis (detailed in Appendix A), 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 forms 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, only a 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. In our study, designers often used basic gestures or arrows on sketches to indicate simple state changes, but these methods were insufficient for fully exhibiting the interaction effects 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 designers' solutions before making choices or improvements (S2).

Customized usage scene (C). Recreating users' life scenarios in the design space serves two purposes. First, it enabled designers to uncover needs that users might have overlooked by observing them in recreated scenarios, 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 as well as 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 to 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 ensures that designers can 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 related to 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 confidence that their understanding is 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 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 for 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, leveraging HoloLens's 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 tests, we conducted separate interviews with the 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 participants' feedback, three key shortcomings of DuoMR 1.0 were identified, leading to the proposal of corresponding design improvements. In following sections, 'D' indicates Designer while 'U' indicates User.

- Challenges of mid-air sketching. All participants 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: Transitioning from mid-air sketching to mid-air modeling to support users to rapidly create 3D models based on gestures.
- Inadequacy in expressing dynamic features. We found that although mid-air sketching enhanced the participants' ability to depict the dynamic effects of the initial and final states, they 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 the 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 that correspond to our 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 these four functions that facilitate co-design.

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

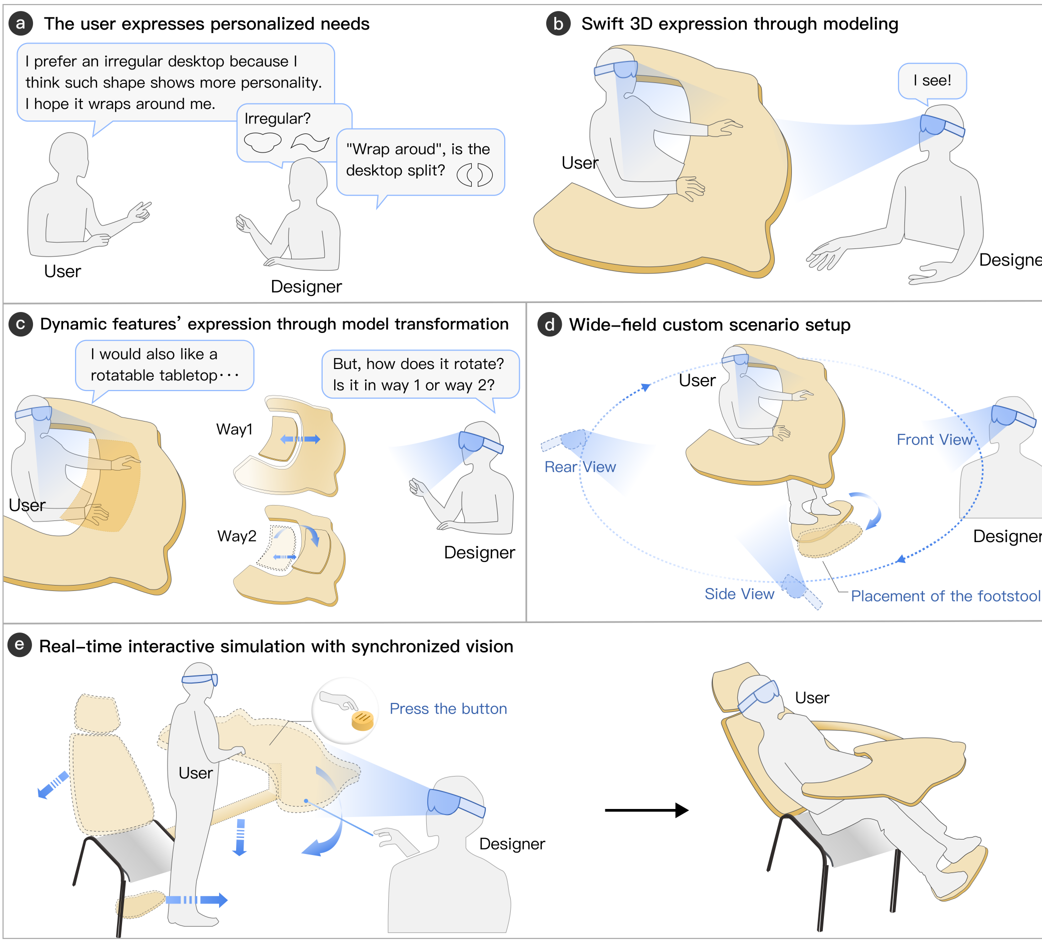

Fig. 1. An example workflow of DuoMR. ⓐ: the user tries to express their requirements for an irregular tabletop; ⓑ: the user creates their desired tabletop shape with DuoMR; ⓒ: the designer utilizes DuoMR to showcase two usage options for the tabletop to the user; ⓓ: the designer adjusts the footrest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

DuoMR supports three modeling commands (i.e. 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. Figures 1ⓐ and 1ⓑ show how the user utilizes DuoMR to quickly demonstrate the desk's shape and its relative position.

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

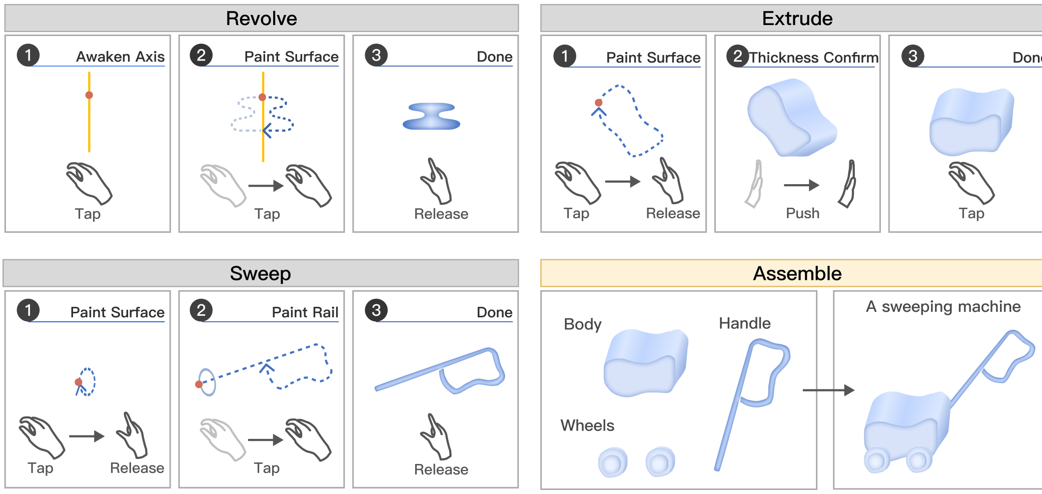

Fig. 2. DuoMR supports three gesture-based modeling commands: revolve, extrude, and sweep. These commands allow designers and users to quickly construct various shapes and then assemble them to form a complete product model.

- **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 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 related to 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 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

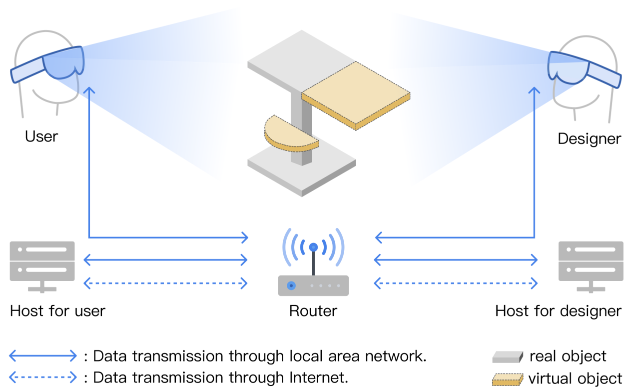

Fig. 3. An illustration of DuoMR's hardware setup and the data transmission. Solid arrows indicate communication between devices for individuals, while dashed arrows denote data synchronization between two persons.

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.

*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. These techniques improve users' comprehension of the product interaction mechanisms, 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 effects 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 sessions, participants wear HoloLens devices connected to individual computers through a local area network for real-time data sharing. In addition, data between the computers is synchronized over the Internet, allowing online plug-in tools to maintain consistent visual perspectives between users and designers.

5.1 Method of Modeling, Editing, and Simulating

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]. For 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

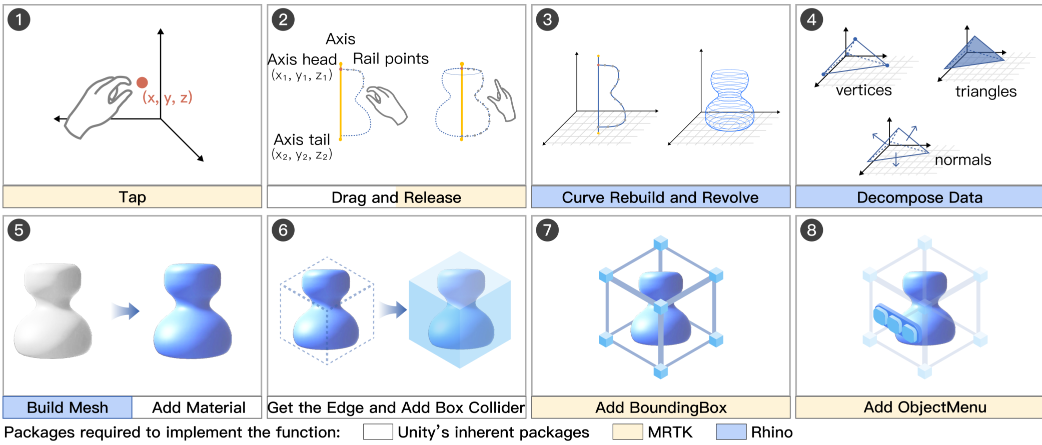

Fig. 4. The implementation of modeling. The color blocks below to each step signify the category of package employed in that specific step. These include: Unity - all packages inherent to Unity; MRTK - all packages from the MRTK toolkit and its expandable packages; Rhino - rhino3dm and compute-rhino3d.

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 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 arises when two HoloLens devices are used simultaneously, as each sets up its own spatial coordinate system, causing discrepancies in the representation of the same physical space.

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 records its position using ASA. Subsequently, the other member's HoloLens accesses this anchor via PUN to synchronize 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.

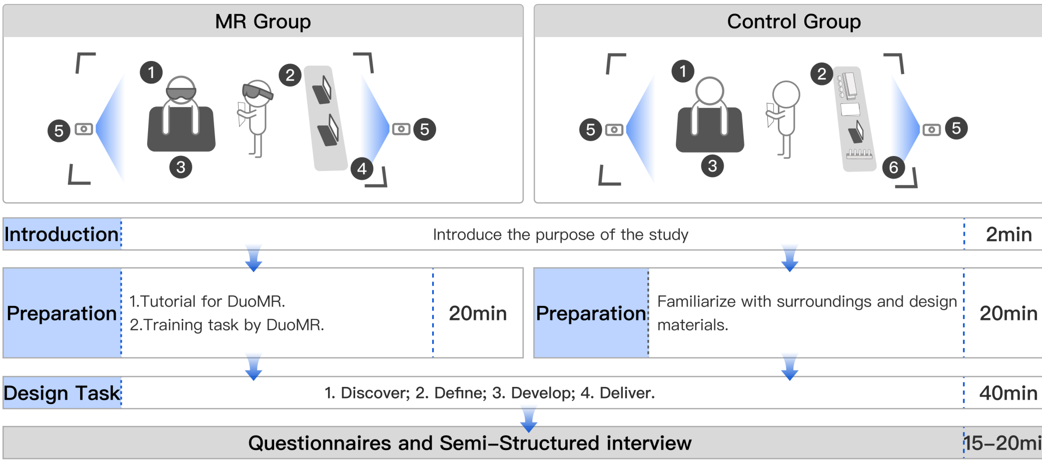

Fig. 5. The experimental setting and procedures of the user study. The area labeled ① refers to the participating user, ② to the participating designer, ③ to the design reference for the design task (a height-adjustable table), ④ to the local server for DuoMR, ⑤ to the recording camera, ⑥ to the design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

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 control group each included 12 designers and 12 users. Designers (9 male and 15 female, aged 20 to 30) were all from design-related fields, 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 shows 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 with 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. Especially, the computers were equipped with common design software like CAD and Rhino. Physical materials and tools included marker pens, cutters, scissors, masking tape, glue, paper, whiteboards, sticky notes, boxboard, foam, modeling clay, and sticks.

Table 2. The questionnaires used in the user study.

Evaluation Content	Questions / Questionnaire
System usability	System Usability Scale [10]
Design process workload	NASA Task Load Index [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.

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's goals and experimental tasks to participants. Participants then familiarized themselves with the experimental environment and design materials. For the control group, participants needed to familiarize themselves with the provided design software and physical materials. For the MR group, participants were required to learn the 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 familiarizing themselves with the system, designers and users in each group collaborated to complete a design task based on the Double Diamond framework [61]. The task involved creating a smart standing desk through four 10-minute stages: Discover, Define, Develop, and Deliver. In the Discover phase, 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 phase, participants used their respective tools to further detail the product's design. Finally, during the Deliver phase, users were encouraged to submit additional requirements based on their experience with the prototype, and designers refined 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 of 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 DuoMR. 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 rated on 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) 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 within the "Good" range, indicating generally positive usability. Designers rated the system slightly higher than users, suggesting that DuoMR aligns better with their workflows. The main factor influencing participants' usability ratings 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], a non-parametric statistical test chosen for its appropriateness in comparing independent samples with non-normally distributed data, to analyze the results. The results are shown in Figure 6.

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 cognitively lighter environment. Similarly, users in the DuoMR setting reported 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 indicating 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. Although 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 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, which required designers to clarify these concepts through sketches, often involving multiple rounds of questioning and revisions. Among the 12 control groups, participants from 10 pairs 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, this pattern changed significantly in the MR group, where users were 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*

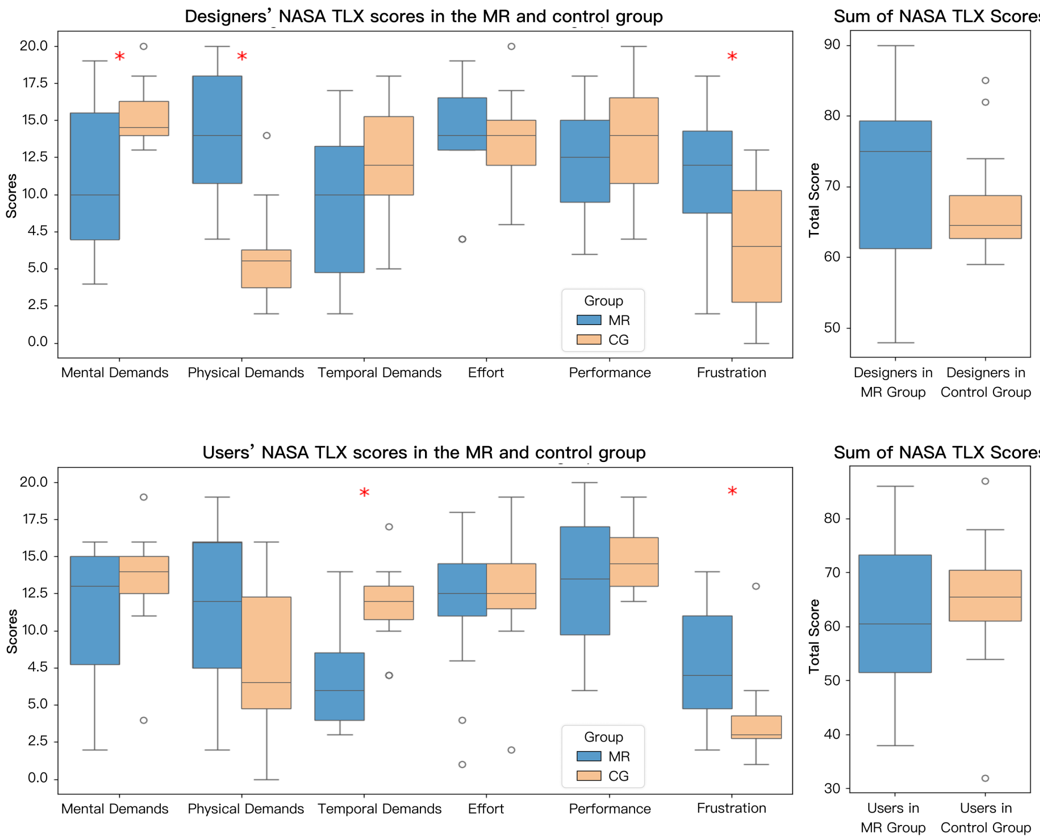

Fig. 6. The NASA TLX scores in the MR and control group. * indicates a significant difference.

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". 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 it."* This explains why users experienced reduced time demands.

6.7 Results: General Communication Satisfaction

Table 3 shows the questions used to evaluate the general communication satisfaction of both users and designers, and Figure 7 displays the corresponding results. We utilized the 16-item Interpersonal Communication Satisfaction Inventory, structured as a 7-point Likert scale questionnaire. Six of these items are reverse-scored questions and marked with a superscript #. As recommended

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

No.	Questions
Q1	The other person let me know that I was communicating effectively.
Q2#	Nothing was accomplished.
Q3	I would like 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.

by Hecht [29], we present the reverse scoring results for these six questions in Figure 7. This indicates that despite the presence of reverse-scored items in the questionnaire, higher scores continue to signify more positive results.

6.7.1 Quantitative Results. Observations from the designers 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 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 easily laugh with their counterparts (Q13). From the users' perspective, we observed 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 communication was more accomplished compared to those in the MR group (Q2). Based on observations, the two groups followed different approaches in the design process. In the MR group, design communication was more oriented toward deeply exploring a limited set of features. Conversely, 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 set 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 for user requirements. From observation notes and interviews, we found that users in the MR group could demonstrate their needs and express their design ideas concretely. This significantly enhanced designers' empathy for 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.

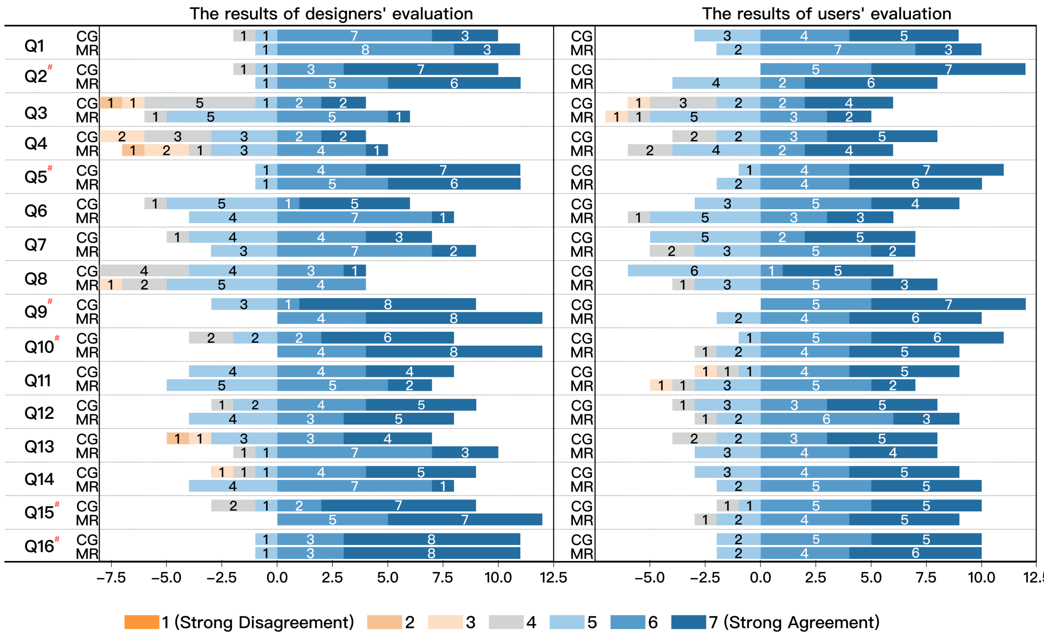

Fig. 7. The results of users' and designers' evaluation on general communication satisfaction. # indicates reversed questions.

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 interpretations through sketches and questioning. CG-D9 said: *"When users expressed themselves using cardboard, I inquired what the cardboard represented and what they intended to convey through it."* In contrast, designers in the MR group could 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 DuoMR, 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 differences in consensus between users and designers regarding 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 were used to visually demonstrate the correlation between users and designers in the two groups. Additionally, we measured the difference in the average distance of the two groups from the line $y = x$ using a t-test. Closer 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, as shown in Figure 8, the MR group clustered in the upper right corner of the chart, indicating an overall higher understanding of needs compared to the control group. In the control group, we observed a horizontal distribution of points in the chart. This suggested that even though designers' assessments of understanding needs varied, users' evaluations were consistent. 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 was observed between the 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 helped users to comprehend the designers' expectations for need collection and redefined what constitutes "good understanding of needs".

Participants in the MR group have higher expectations for design proposals. Participants in the MR group believed that an effective design dialogue should cover specific aspects of products. For instance, they focused on aspects such as 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 was not because participants in the control group considered these aspects unimportant, but because they felt the materials provided in the experiment were insufficient for discussing 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 could be due 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 only briefly into each one. For instance, the third pair 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, according to CG-U3: *"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. For example, the second pair in the MR group designed a foldable

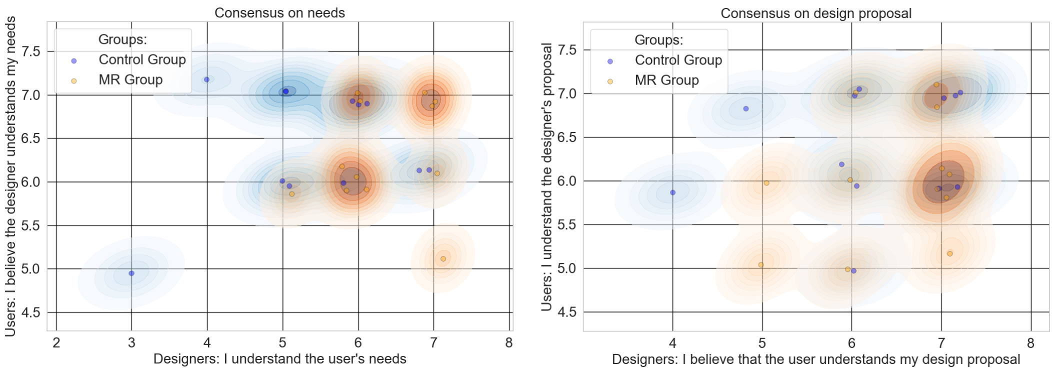

Fig. 8. Consensus between users and designers on needs and design proposals. Left: Consensus on needs; Right: Consensus on design proposals.

tabletop, a rack with telescopic mechanical rods, and an extra vertical monitor. Their discussions delved deeply into the mechanical rods, covering the position, size, and different ways to control each rod. MR-U2 described the effectiveness of using DuoMR to discuss features, stating: *"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 used representations. Specifically, in the control group, participants used both 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 MR allowed participants to discuss new elements, such as the product's complete interaction process and related ergonomics. Although both groups were explicitly asked 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), and believed that the complete interaction path, including operational methods and product feedback, was never 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 how the product interacted with 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."*

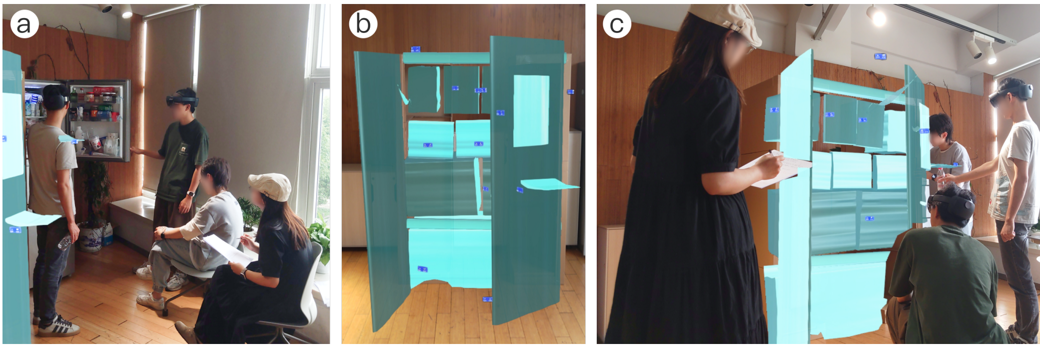

Fig. 9. The illustration of the practical application case. ⓐ: team members observed the actual use of the refrigerator; ⓑ: models were created with DuoMR during the discussion; ⓒ: team members refined and iterated on design ideas based on the created models.

7 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 a design team consisting of four participants to test the system. We examined how DuoMR influences design discussions involving multiple stakeholders in practical settings.

7.1 Research Context

The design team included an industrial designer, an engineering designer, a CMF (color, material, and finish) designer, and a user. They were invited to design a refrigerator specifically for use in the company lounge. Unlike household refrigerators, those in a company lounge cater to multiple people with varied habits, primarily store beverages and snacks, and require 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 revealed new advantages of DuoMR. Specifically, we found that when 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 is 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 immediately 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 adjust the design."* 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 facilitated 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 were able to 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, enabling the estimation of its physical properties and selection of the appropriate materials."* Therefore, DuoMR's 3D visualization capabilities significantly enhance the efficiency of cross-disciplinary knowledge exchange and comprehension.

8 Discussion

8.1 The Distinctions Between DuoMR and Other Design Support Systems

Although DuoMR allows users to participate in design similarly to designers, its primary role is to improve communication efficiency between users and designers, rather than to lower the design barrier. Many existing approaches aim to reduce the design barrier. 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 expressing 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 often 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. By 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 enhances 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 integration into 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, MR group members immediately experimented with 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 the proposed system. While the system exhibits promising capabilities for various forms of concrete, dynamic, and experience-based communication, it also exposes limitations that warrant further exploration.

First, providing features tailored to 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 should investigate the diverse needs of design teams and further examine MR's capabilities to facilitate communication in multi-role scenarios.

Second, improving the application of MR technology in later design stages can enhance its integration into traditional design processes. Although DuoMR supports early design and prototyping, designers currently rely on photographs to retain information before reverting to conventional methods for later 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 increases user 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. Based on the findings from a formative study, we designed and developed DuoMR to aid 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 a synchronized view. Results from the user study and practical case study indicate that DuoMR effectively reduces cognitive load during communication and enhances mutual understanding.

Acknowledgments

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References

[1] Jimmy Abualdenien and André Borrmann. 2020. Vagueness visualization in building models across different design stages. *Advanced Engineering Informatics* 45 (2020), 101107.

[2] Jorge Alcaide-Marzal, José Antonio Diego-Más, Sabina Asensio-Cuesta, and Betina Piqueras-Fiszman. 2013. An exploratory study on the use of digital sculpting in conceptual product design. *Design Studies* 34, 2 (2013), 264–284.

[3] Rahul Arora, Rubaiat Habib Kazi, Tovi Grossman, George Fitzmaurice, and Karan Singh. 2018. Symbiosissketch: Combining 2d & 3d sketching for designing detailed 3d objects in situ. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–15.

[4] Rahul Arora, Rubaiat Habib Kazi, Danny M Kaufman, Wilmot Li, and Karan Singh. 2019. Magicalhands: Mid-air hand gestures for animating in vr. In *Proceedings of the 32nd annual ACM symposium on user interface software and technology*. 463–477.

[5] Bita Astaneh Asl, Wendy Nora Rummerfield, and Carrie Sturts Dossick. 2023. Effects of virtual reality on complex building system recall. In *Virtual Worlds*, Vol. 2. MDPI, 203–217.

[6] Microsoft Azure. 2022. Azure Spatial Anchors | Microsoft Azure. Retrieved July 17, 2023 from https://azure.microsoft.com/en-us/products/spatial-anchors/

[7] Aaron Bangor, Philip T Kortum, and James T Miller. 2008. An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction* 24, 6 (2008), 574–594.

[8] Fatma Ben Guefrech, Jean-François Boujut, Elies Dekoninck, and Gaetano Cascini. 2023. Studying interaction density in co-design sessions involving spatial augmented reality. *Research in Engineering Design* 34, 2 (2023), 201–220.

[9] Jean-François Boujut and Pascal Laureillard. 2002. A co-operation framework for product–process integration in engineering design. *Design studies* 23, 6 (2002), 497–513.

[10] John Brooke et al. 1996. SUS-A quick and dirty usability scale. *Usability evaluation in industry* 189, 194 (1996), 4–7.

[11] Bill Buxton. 2010. *Sketching user experiences: getting the design right and the right design.* Morgan kaufmann.

[12] Philip Cash and Anja Maier. 2021. Understanding representation: Contrasting gesture and sketching in design through dual-process theory. *Design Studies* 73 (2021), 100992.

[13] Maral Babapour Chafi. 2014. Roles of externalisation activities in the design process. *Swedish Design Research Journal* 11 (2014), 34–46.

[14] Young Mi Choi, Sanchit Mittal, et al. 2015. Exploring benefits of using augmented reality for usability testing. In *DS 80-4 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 4: Design for X, Design to X, Milan, Italy, 27-30.07. 15*. 101–110.

[15] Nigel Cross. 1999. Natural intelligence in design. *Design studies* 20, 1 (1999), 25–39.

[16] Françoise Detienne and Willemien Visser. 2006. Multimodality and parallelism in design interaction: co-designers' alignment and coalitions. *Frontiers in Artificial Intelligence and Applications* 137 (2006), 118.

[17] Ellen Yi-Luen Do. 2005. Design sketches and sketch design tools. *Knowledge-Based Systems* 18, 8 (2005), 383–405.

[18] Yujia Du, Kexiang Liu, Yuxin Ju, and Haining Wang. 2023. A comfort analysis of AR glasses on physical load during long-term wearing. *Ergonomics* 66, 9 (2023), 1325–1339.

[19] Kenneth D Eason. 1995. User-centred design: for users or by users? *Ergonomics* 38, 8 (1995), 1667–1673.

[20] Pelle Ehn. 1988. *Work-oriented design of computer artifacts.* Ph. D. Dissertation. Arbetslivscentrum.

[21] Pelle Ehn. 2017. Scandinavian design: On participation and skill. In *Participatory design.* CRC Press, 41–77.

[22] Photon Engine. 2018. Multiplayer Game Development Made Easy | Photon Engine. Retrieved August 28, 2023 from https://www.photonengine.com/

[23] Jodi Forlizzi and Cherie Lebbon. 2002. From formalism to social significance in communication design. *Design issues* 18, 4 (2002), 3–13.

[24] Erin Friess. 2010. The sword of data: Does human-centered design fulfill its rhetorical responsibility? *Design issues* 26, 3 (2010), 40–50.

[25] Lorenzo Giunta, Fatma Ben Guefrache, Elies Dekoninck, James Gopsill, Jamie O'Hare, and Federico Morosi. 2019. Investigating the impact of spatial augmented reality on communication between design session participants-A pilot study. In *Proceedings of the Design Society: International Conference on Engineering Design*, Vol. 1. Cambridge University Press, 1973–1982.

[26] Vinod Goel. 1995. *Sketches of thought.* MIT press.

[27] Ramy Hammady, Minhua Ma, and Carl Strathearn. 2019. User experience design for mixed reality: a case study of HoloLens in museum. *International Journal of Technology Marketing* 13, 3-4 (2019), 354–375.

[28] Sandra G Hart. 2006. NASA-task load index (NASA-TLX); 20 years later. In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 50. Sage publications Sage CA: Los Angeles, CA, 904–908.

[29] Michael L Hecht. 1978. The conceptualization and measurement of interpersonal communication satisfaction. *Human Communication Research* 4, 3 (1978), 253–264.

[30] Kathryn Henderson. 1998. *On line and on paper: Visual representations, visual culture, and computer graphics in design engineering.* MIT press.

[31] Hal W Hendrick. 1991. Ergonomics in organizational design and management. *Ergonomics* 34, 6 (1991), 743–756.

[32] Morris B Holbrook and William L Moore. 1981. Feature interactions in consumer judgments of verbal versus pictorial presentations. *Journal of consumer research* 8, 1 (1981), 103–113.

[33] David G Jansson and Steven M Smith. 1991. Design fixation. *Design studies* 12, 1 (1991), 3–11.

[34] Ruoyu Jin, Tong Yang, Poorang Piroozfar, Byung-Gyoo Kang, Dariusz Wanatowski, Craig Matthew Hancock, and Llewellyn Tang. 2018. Project-based pedagogy in interdisciplinary building design adopting BIM. *Engineering, Construction and Architectural Management* 25, 10 (2018), 1376–1397.

[35] Tom Kelley. 2001. Prototyping is the shorthand of innovation. *Design Management Journal (Former Series)* 12, 3 (2001), 35–42.

[36] Maaike Kleinsmann and Andy Dong. 2007. Investigating the affective force on creating shared understanding. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Vol. 48043. 115–124.

[37] Wiesław Kopeć, Marcin Wichrowski, Krzysztof Kalinowski, Anna Jaskulska, Kinga Skorupska, Daniel Cnotkowski, Jakub Tyszka, Agata Popieluch, Anna Voitenkova, Rafał Masłyk, et al. 2019. VR with older adults: participatory design of a virtual ATM training simulation. *IFAC-PapersOnLine* 52, 19 (2019), 277–281.

[38] Carlye A Lauff, Daniel Knight, Daria Kotys-Schwartz, and Mark E Rentschler. 2020. The role of prototypes in communication between stakeholders. *Design Studies* 66 (2020), 1–34.

[39] Bokyung Lee, Minjoo Cho, Joonhee Min, and Daniel Saakes. 2016. Posing and acting as input for personalizing furniture. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction.* 1–10.

[40] Bokyung Lee, Joongi Shin, Hyoshin Bae, and Daniel Saakes. 2018. Interactive and situated guidelines to help users design a personal desk that fits their bodies. In *Proceedings of the 2018 designing interactive systems conference.* 637–650.

[41] Julie S Linsey, Ian Tseng, Katherine Fu, Jonathan Cagan, Kristin L Wood, and Christian Schunn. 2010. A study of design fixation, its mitigation and perception in engineering design faculty. (2010).

[42] Rachael Luck. 2014. Seeing architecture in action: Designing, evoking, and depicting space and form in embodied interaction. *International journal of design creativity and innovation* 2, 3 (2014), 165–181.

[43] Weizhou Luo, Anke Lehmann, Hjalmar Widengren, and Raimund Dachselt. 2022. Where should we put it? layout and placement strategies of documents in augmented reality for collaborative sensemaking. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems.* 1–16.

[44] Patrizia Marti and Liam J Bannon. 2009. Exploring user-centred design in practice: Some caveats. *Knowledge, technology & policy* 22 (2009), 7–15.

[45] Tara Matthews, Tejinder Judge, and Steve Whittaker. 2012. How do designers and user experience professionals actually perceive and use personas?. In *Proceedings of the SIGCHI conference on human factors in computing systems.* 1219–1228.

[46] Robert McNeel. 2020. Rhino - Compute Guides. Retrieved May 12, 2023 from https://developer.rhino3d.com/guides/compute/

[47] Robert McNeel. 2021. NuGet Gallery | Rhino3dm 7.15.0. Retrieved May 12, 2023 from https://www.nuget.org/packages/Rhino3dm/

[48] Xin Min, Wenqiao Zhang, Shouqian Sun, Nan Zhao, Siliang Tang, and Yueting Zhuang. 2019. VPModel: High-fidelity product simulation in a virtual-physical environment. *IEEE transactions on visualization and computer graphics* 25, 11 (2019), 3083–3093.

[49] Michael J Muller and Sarah Kuhn. 1993. Participatory design. *Commun. ACM* 36, 6 (1993), 24–28.

[50] Keith M Murphy. 2005. Collaborative imagining: The interactive use of gestures, talk, and graphic representation in architectural practice. (2005).

[51] Nadim Nachar et al. 2008. The Mann-Whitney U: A test for assessing whether two independent samples come from the same distribution. *Tutorials in quantitative Methods for Psychology* 4, 1 (2008), 13–20.

[52] Donald A Norman and Andrew Ortony. 2003. Designers and users: Two perspectives on emotion and design. In *Symposium on foundations of interaction design*. Interaction Design Institute, 1–13.

[53] DJ Osbourne, Fernando Leal, Rene Saran, Pat Shipley, and Tom Stewart. 2014. *Person-centred ergonomics: a Brantonian view of human factors*. CRC Press.

[54] Eujin Pei, Ian Campbell, and Mark Evans. 2011. A taxonomic classification of visual design representations used by industrial designers and engineering designers. *The Design Journal* 14, 1 (2011), 64–91.

[55] polar kev. 2022. MRTK2-Unity Developer Documentation - MRTK 2 | Microsoft Learn. Retrieved August 15, 2023 from https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2

[56] A Terry Purcell and John S Gero. 1996. Design and other types of fixation. *Design studies* 17, 4 (1996), 363–383.

[57] Charlie Ranscombe and Katherine Bissett-Johnson. 2017. Digital Sketch Modelling: Integrating digital sketching as a transition between sketching and CAD in Industrial Design Education. *Design And Technology Education: An International Journal* 22, 1 (2017), 1–15.

[58] Holger T Regenbrecht, Michael Wagner, and Gregory Baratoff. 2002. Magicmeeting: A collaborative tangible augmented reality system. *Virtual Reality* 6 (2002), 151–166.

[59] Yoram Reich, Suresh L Konda, Ira A Monarch, Sean N Levy, and Eswaran Subrahmanian. 1996. Varieties and issues of participation and design. *Design Studies* 17, 2 (1996), 165–180.

[60] Toni Robertson and Jesper Simonsen. 2012. Challenges and opportunities in contemporary participatory design. *Design Issues* 28, 3 (2012), 3–9.

[61] Alan M Rugman and Joseph R D'cruz. 1993. The" double diamond" model of international competitiveness: The Canadian experience. *MIR: Management International Review* (1993), 17–39.

[62] EBN Sanders. 2006. Nurse and patient participatory workshops for the NBBJ project. *Inpatient tower expansion for H. Lee Moffitt Cancer Center and Research Institute, Tampa, FL, USA* (2006).

[63] Elizabeth BN Sanders. 2006. Design research in 2006. *Design research quarterly* 1, 1 (2006), 1–8.

[64] Elizabeth B-N Sanders. 2002. From user-centered to participatory design approaches. In *Design and the social sciences*. CRC Press, 18–25.

[65] Elizabeth B-N Sanders and Pieter Jan Stappers. 2008. Co-creation and the new landscapes of design. *Co-design* 4, 1 (2008), 5–18.

[66] Steven Schkolne, Michael Pruett, and Peter Schröder. 2001. Surface drawing: creating organic 3D shapes with the hand and tangible tools. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 261–268.

[67] Jesper Simonsen and Toni Robertson. 2012. *Routledge international handbook of participatory design*. Routledge.

[68] Martin Sole, Patrick Barber, Ian Turner, et al. 2021. Mechanical Engineering Design, Does the Past Hold the key to the Future?. In *DS 110: Proceedings of the 23rd International Conference on Engineering and Product Design Education (E&PDE 2021), VIA Design, VIA University in Herning, Denmark. 9th-10th September 2021*.

[69] Masaki Suwa and Barbara Tversky. 1997. What do architects and students perceive in their design sketches? A protocol analysis. *Design studies* 18, 4 (1997), 385–403.

[70] John C Tang. 1991. Findings from observational studies of collaborative work. *International Journal of Man-machine studies* 34, 2 (1991), 143–160.

[71] Unity Technologies. 2022. Unity 2020.3.36. Retrieved March 7, 2023 from https://unity.com/releases/editor/whats-new/2020.3.36

[72] M Veveris. 1994. The importance of the use of physical engineering models in design. In *IDATER 1994 Conference, Loughborough: Loughborough University*. Citeseer.

[73] John Vines, Rachel Clarke, Peter Wright, John McCarthy, and Patrick Olivier. 2013. Configuring participation: on how we involve people in design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 429–438.

[74] Eric Von Hippel. 2006. *Democratizing innovation*. the MIT Press.

[75] Kexing Wang, Zhenlin Song, Xuanhui Liu, Pei Chen, and Lingyun Sun. 2023. Using AR HMD in exhibition: Effects of guidance methods and spatial relative positions. In *IASDR 2023: Life-Changing Design*, D. De Sainz Molestina, L. Galluzzo, F. Rizzo, and D. Spallazzo (Eds.).

[76] Xiangyu Wang and Phillip S Dunston. 2011. Comparative effectiveness of mixed reality-based virtual environments in collaborative design. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 41, 3 (2011), 284–296.

[77] Zeyu Wang, Cuong Nguyen, Paul Asente, and Julie Dorsey. 2023. PointShopAR: Supporting Environmental Design Prototyping Using Point Cloud in Augmented Reality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–15.

[78] Christian Weichel, Manfred Lau, David Kim, Nicolas Villar, and Hans W Gellersen. 2014. MixFab: a mixed-reality environment for personal fabrication. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 3855–3864.

[79] Justin D Weisz, Michael Muller, Jessica He, and Stephanie Houde. 2023. Toward general design principles for generative AI applications. *arXiv preprint arXiv:2301.05578* (2023).

[80] Matt Whitlock, Jake Mitchell, Nick Pfeufer, Brad Arnot, Ryan Craig, Bryce Wilson, Brian Chung, and Danielle Albers Szafir. 2020. MRCAT: In situ prototyping of interactive AR environments. In *International Conference on Human-Computer Interaction*. Springer, 235–255.

[81] Deborah Lynne Wiley. 2007. Outside innovation: How your customers will co-design your company's future.

[82] D Winske and Nagendra Omidi. 1991. Hybrid codes: Methods and applications. *Presented at the 4th International School for Space Simulation* (1991), 1–5.

[83] Zhijie Xia, Kyzyl Monteiro, Kevin Van, and Ryo Suzuki. 2023. RealityCanvas: Augmented Reality Sketching for Embedded and Responsive Scribble Animation Effects. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. 1–14.

[84] Baoxuan Xu, William Chang, Alla Sheffer, Adrien Bousseau, James McCrae, and Karan Singh. 2014. True2Form: 3D curve networks from 2D sketches via selective regularization. *ACM Transactions on Graphics* 33, 4 (2014).

[85] Maria C Yang. 2005. A study of prototypes, design activity, and design outcome. *Design Studies* 26, 6 (2005), 649–669.

[86] Kevin Yu, Ulrich Eck, Frieder Pankratz, Marc Lazarovici, Dirk Wilhelm, and Nassir Navab. 2022. Duplicated reality for co-located augmented reality collaboration. *IEEE Transactions on Visualization and Computer Graphics* 28, 5 (2022), 2190–2200.

A Interview Outline for the formative study

Table 4. The outlines for interview questions with designers and users in the 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 designer's ideas?
Requirement consensus	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?

Table 5. The coding results (Part 1). '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 the 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."*

Table 6. The coding results (Part 2). 'D' stands for 'Designer' and 'U' denotes 'User' (continue).

Codes	Explanation with quotes
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."*

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