MR-CoCo: An Open Mixed Reality Testbed for Co-located Couple Product Configuration and Decision-Making – A Sailboat Case Study

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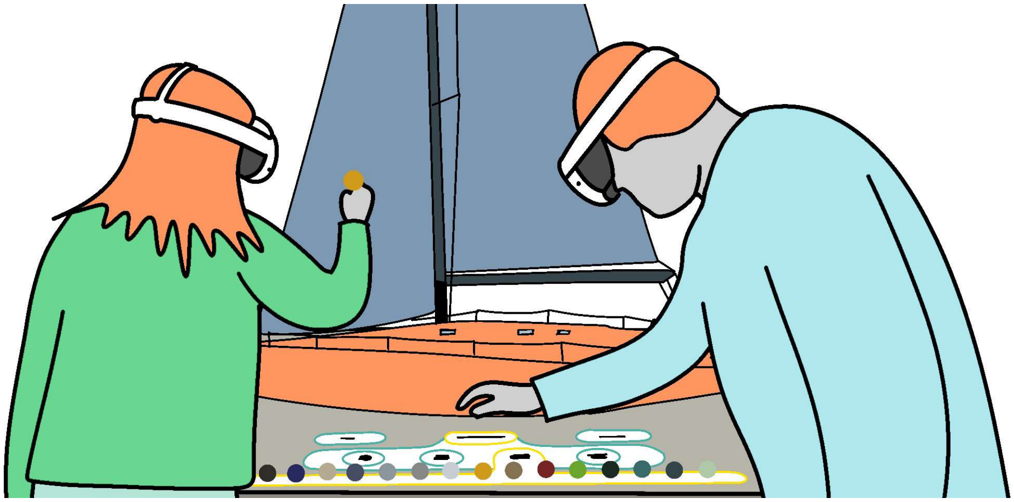

Fig. 1: **MR-CoCo testbed**: Co-located Couple Product Configurator in Mixed Reality. Two users (couple) simultaneously configure a virtual sailboat on a physical table, manipulating and customizing materials through the interaction with draggable UI spheres within the mixed reality environment.

Abstract—The literature has demonstrated the advantages of Mixed Reality (MR) for product configuration by providing a more engaging and effective end-user experience. While collaborative and remote design tools in MR have been widely explored in previous studies, a noticeable gap remains in the exploration of co-located product configuration for couples. This gap is noteworthy since in many industries, couples (e.g., friends, partners) often make purchasing decisions together in physical retail environments. In this paper, we introduce MR-CoCo, an open MR testbed designed to explore collaborative configurations by co-located couples, both in the role of customers. The testbed is developed in Unity and features: (i) a shared MR space with virtual product 3D model anchoring, (ii) shared visualization of the current configuration, (iii) a versatile UI for selecting configuration areas, (iv) hand gestures for 3D drag and drop of colors and materials from 3D catalog to the product. A case study of the personalization of a sailboat is provided as proof of concept. The user study involved 24 couples (48 participants in total), simulating a purchasing experience and the related configuration using MR-CoCo. We assessed usability through post-experience evaluations, with the System Usability Scale (SUS) and the Co-Presence Configuration Questionnaire (CCQ) to measure collaboration and decision-making. The results demonstrated a high level of usability and perceived quality of collaboration. We also explore guidelines that can be used for remote collaboration applications, enabling configuration across a wide range of industries (e.g., automotive and clothing).

Index Terms—Product configuration, co-located, multi-user, collaboration, co-presence, user study, mixed reality.

1 Introduction

Modern products often feature a higher configuration level, achieved through mass customization technology or high-end craftsmanship. The primary objective of product configurators is to enable users to personalize products by selecting materials, colors, shapes, and other features while simultaneously showcasing the product's attributes [9, 27, 44]. This process involves deciding whether structural components, room layouts, or aesthetic details [1, 18, 50].

Recently, product configurators have expanded across various industries, including automotive, construction, and nautical [16, 29, 41]. These tools primarily enable users to customize complex products, often on 2D and e-commerce platforms [49]. We selected nautical products as a case study, as this sector provides a compelling opportunity to explore the intersection of advanced technology and a traditional yet critical part of the global economy. Moreover, it involves intricate models with multiple components that can be individually customized to meet clients' preferences. However, conventional product configurators are limited in terms of immersion and multi-user capabilities [4, 32]. A lack of real-time feedback and a poor user experience can lead to longer decision-making processes, increased costs, and eventually result in lost sales and customer dissatisfaction [48].

The use of Mixed Reality (MR) in product configurators can significantly enhance the user experience and alleviate the challenges faced by conventional methods [1, 11, 22, 30]. MR allows users to perceive the same physical space and alignment, enabling faster and more engaging

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decision-making [2,24]. By incorporating passthrough technology, MR creates an advanced, real-life configuration process, ensuring that the couple is not isolated but has a more social and interactive experience, similar to that in expos or showrooms.

Product configuration often requires decision-making and collaboration among two or more individuals, whether between business partners, a client and a designer, or a salesperson and a customer [15,26,47]. Many industries use co-decision workflows—from yacht design to interior architecture, where two professionals collaborate on design choices. The couple's collaboration has a common goal, mutual support, and a diversity of competencies. Positive communication and mutual trust play a crucial role in successful teamwork, but can also conflict with poor communication [6,36,46]. It is crucial to maintain a collaborative advantage of the couple configuration in dynamic and technologically advanced solutions [14,35].

Prior literature with comparative studies dedicated to product configurations has demonstrated the superiority of immersive technologies over 2D interfaces in terms of engagement, spatial cognition, and user satisfaction [17,38,43]. This work addresses a real industry problem with a novel framework and study that has no similar of its kind. Therefore, we present a feasibility evaluation. Moreover, previous studies have focused primarily on individual configuration experiences or remote collaboration [13], a research gap remains regarding intuitive interaction approaches that align with the multi-user tasks. Without a defined testbed, users often struggle to complete complex configuration processes efficiently, resulting in frustration and reduced productivity.

Our study explores how MR can enhance collaborative product customization in co-located settings, particularly in industries such as marine, caravan, and automotive, where products are highly customizable and not readily available for immediate inspection. In these cases, buyers, often couples, must rely on abstract representations or limited samples, which can undermine confidence in the decision-making process.

MR-CoCo is an open framework to study co-located couple product configuration by using MR technology. The system enables the display of a real-time, immersive product visualization and configuration interface for the couple, leveraging the presence of real-world context, including face-to-face interactions, verbal communication, gestures, environment, and mutual feedback from the couple (e.g., nodding, contempt, awe, etc.). To the best of our knowledge, this framework is one of the first studies supporting this kind of multi-user task, although it's a common situation in retail where couples visit a store or a facility and want to decide together on complex and configurable products (e.g., cars, boats, houses, etc.). The open framework provides a shared 3D user interface and a real-time preview of the current configuration. The possibility to interact with the other user in an unfiltered and natural way can overcome technology shyness [25,37], Virtual Reality (VR) adaptation issues [21], and overall improve the user's acceptance. The framework is designed to be versatile in replacing the product to be configured and is intended for use by other researchers or developers to be applied in other industrial sectors or to study couple interaction.

Therefore, the contributions of this work are as follows:

- highlighting the industrial importance of co-located couple product configuration as an unexplored research topic,
- presenting implementations of the open framework on Co-locate couple configuration (can be used by other researchers),
- providing a case study in sailboat design with qualitative metrics.

2 Related Works

This section reviews the previous work in two key areas relevant to MR-CoCo: **1. MR Product Configurators**, and **2. Co-located Multi-User MR Systems**.

2.1 MR Product Configurators

Product configuration systems have evolved from static web-based interfaces to more dynamic 3D and immersive platforms. Traditional 2D configurators typically allow users to customize aspects such as materials or colors, but often lack spatial immersion or support for collaborative workflows [44,49].

Recent advancements have extended configurators into immersive VR, enabling users to interact with 3D models. For instance, Jin et al. [23] introduced a VR-based product configurator that improves user engagement by providing an interactive environment for collaborative decision-making. However, these VR-based approaches often focus on scaled product representations, limiting real-world spatial alignment and interaction.

Similarly, Piccininni et al. [33] presented MAGIC, A multi-user customization scenario in high-end domains, including yacht design, by incorporating photorealistic rendering and ergonomic evaluation. While these systems improve immersion and realism, they still fall short in facilitating synchronized, real-time collaboration within a shared physical space.

MR-CoCo diverges from these previous solutions by offering a hybrid Mixed Reality (MR) approach that integrates virtual elements into the user's real-world environment, providing a more immersive and contextually grounded experience. Unlike traditional VR-based systems, which often rely on asynchronous feedback or remote collaboration, MR-CoCo ensures real-time, synchronized co-creation. By leveraging spatial anchors and dynamic interfaces, MR-CoCo enables seamless interaction among users, overcoming common challenges in prior MR tools, such as physical misalignment and asynchronous feedback in systems like Arkio [8] and Fages et al. [10].

This integration of real-time collaboration and spatial awareness marks a significant step forward in MR-based product configurators, addressing gaps left by systems that emphasize either physical or virtual worlds without ensuring synchronized co-location.

2.2 Co-located Multi-User MR Systems

Co-located MR enables users to interact with shared virtual objects while maintaining a sense of physical presence, which has been shown to improve collaboration, communication, and task coordination [28,45]. Unlike remote setups where collaboration relies on avatars and abstracted cues [34], co-located MR promotes natural visual and verbal exchanges.

Previous work has explored the role of user positioning in enhancing collaborative MR experiences. Studies suggest that arrangements such as side-by-side positioning can improve accessibility but may introduce interference in shared workspace [39]. For instance, research extending Fitts' Law to multi-user VR collaboration has shown that physical proximity can facilitate interaction but also create challenges in terms of spatial overlap and interference in the workspace [7,40].

In the context of collaboration within immersive environments [20], full support for collaboration and direct communication between users is essential for completing a collaborative task. This highlights the importance of designing games in collaborative virtual environments that facilitate communication without relying solely on text or audio.

Similarly, Norman et al. [31] explored multi-user augmented reality (AR) collaboration, where a remote supervisor assisted two co-located users in designing room layouts. Although effective, challenges such as interaction fluidity and object manipulation accuracy were observed. While these studies have explored functional and technical collaboration within co-located AR and VR environments, few have specifically addressed the dynamics of collaborative decision-making, particularly in contexts requiring aesthetic or design-oriented judgment.

MR-CoCo fills this gap by focusing on synchronized co-located customization, enabling real-time mutual awareness among multiple users engaged in aesthetic decision-making. This approach contrasts with prior work, such as that by Sereno et al. [42], which primarily categorizes AR collaboration along functional lines. MR-CoCo's integration of real-time aesthetic decision-making offers a more intuitive and engaging process compared to prior studies focused on technical collaboration.

Moreover, commercial solutions like Arkio [8] demonstrate the potential for co-located collaboration in architectural design but remain constrained by preset asset libraries and limited customization capabilities. In contrast, MR-CoCo enables freeform, user-driven customiza-

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tion with real-time feedback, pushing the boundaries of co-located MR experiences beyond predefined design frameworks.

Despite growing interest in immersive collaboration, significant gaps remain in the domain of co-located aesthetic product configuration. Much of the existing literature has focused on remote or functional collaboration, often overlooking the more nuanced, interactive decision-making processes that are essential in real-time aesthetic customization. MR-CoCo represents a novel framework by integrating co-presence, spatial interaction, and immersive customization. This integration offers a more effective, intuitive, and engaging collaborative design experience compared to prior solutions, which have not simultaneously emphasized co-location, aesthetic decisions, and configurability in a modular framework.

3 MR-CoCo Testbed Design

We present MR-CoCo, a proof-of-concept and open testbed for a dual-user MR product configurator that operates in real-time within a shared virtual space. This research focuses on the interaction between two users during the configuration of a virtual model, utilizing a sailboat case study centered on material selection. The system enables natural hand interactions and provides visual feedback, facilitating informed decision-making and enriching the configuration experience.

MR-CoCo is a MR product configuration application designed for couples Fig. 1. It leverages augmentation to display 3D product visualizations and a 3D interface in a real-world context. The primary function of the system is to provide a shared 3D user interface that allows both users, in the role of collaborative customers, to configure the material combination on a virtual 3D model and receive a real-time shared preview. Despite the virtual nature of the scenario, the advantage of augmentation lies in preserving a strong sense of presence in the real world (e.g., a store, meeting room, or showroom), enhancing the collaborative experience.

The MR-CoCo platform was conceived as an extremely modular and adaptable test bed, capable of supporting numerous configuration scenarios that go beyond specific use cases or product types. Thanks to this modular architecture, it is possible to test collaborative workflows in the most diverse retail environments, abstracting assets and logics specific to each scenario. MR-CoCo enables rapid adaptation to different case studies by the following steps:

1. Import CAD model into Unity MRCOCO project and insert inside the "MODEL HERE" node hierarchy;
2. Import or create the configuration materials (e.g., texture, colors, etc.);
3. Customize UI (labels and icons) according to the desired theme Fig. 2;
4. Connect the material widget (3D UI spheres) to the material in the model by unity inspector.

More detailed instructions are available in the Testbed readme file.

3.1 Interface design

The MR-CoCo interface has been structured following an iterative design approach to provide an intuitive and immersive collaborative experience. The interface is organized hierarchically, supporting step-by-step navigation. Both users can interact with the virtual model simultaneously, applying changes and observing each other's actions in real-time. This collaborative model simulates physical interaction within a shared space, making the configuration process more natural and efficient. The interface eliminates the need for controllers, emphasizing hand tracking for interaction. The menu structure is divided into three distinct rows, each corresponding to different customization functionalities Fig. 2.

1. **First Row:**
   - *State Control Button (Left):* This button allows users to toggle between internal and external views of the target object in a split-screen format and to change the state of the main block.
   - *Category/Group Selection (Right):* Users can select the primary category or group of configurable elements for the model.
2. **Second Row:** *Subcategory Selection:* This row enables the user to select specific subcategories of configurable objects.
3. **Third Row:** *Color Palette:* Users can select predefined colors from a palette and drag them onto target components to modify their appearance in real-time.

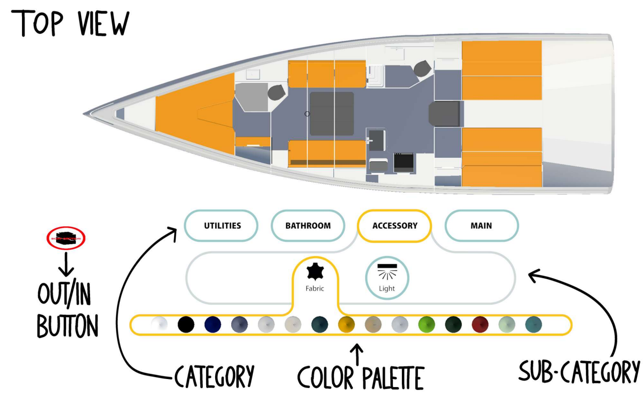

Fig. 2: **MR-CoCo interface** (Top view): The interface features a three-row menu for category selection, subgroup refinement, and color application. A side button allows users to toggle between internal and external views of the model.

3.1.1 Interactions

User interaction in MR-CoCo is designed to rely primarily on hand tracking, with the controller being used solely for initial co-location setup. The system's interactions are as follows:

Selection of UI:

- *User Interface Interaction* Users can interact with UI elements using hand gestures, specifically through index finger gestures. The controller is used only for the initial space anchor setup phase. After the setup, interactions are facilitated through hand tracking. The custom script "Toggle" is used to synchronize the activation and deactivation of the interface when interacting with the index finger.
- *Perspective Switch interaction:* Users can toggle between internal and external views of the product being configured. This perspective switch enhances user understanding of the space and supports collaborative discussions by offering different perspectives on the model.

Material configuration: The system enables users to apply predefined colors to various components of the virtual model in real-time. This feature facilitates collaborative exploration of material combinations, enabling users to jointly determine the final configuration. Users apply colors by selecting a color sphere via a "pinch" gesture and dragging it onto the corresponding target component. Upon collision with a configurable surface, the color is applied in real-time, and audio feedback confirms the successful application. The "Photon Grabbable Object" component script and the custom "DraggableSphere" script ensure that the sphere behaves appropriately within the virtual environment and that the color change is synchronized between both users.

3.2 System Design

The MR-CoCo testbed is designed to support real-time multi-user collaboration. It comprises two primary components: the software component, which integrates the information-sharing functionality, and the hardware component, which handles user positioning and device support Fig. 4.

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Fig. 3: **Couple Interaction in Shared VR Environment**: From the first user's perspective, the second user configures the color of the virtual sailboat via the shared user interface, which is rendered simultaneously.

3.2.1 Software

MR-CoCo is implemented using Unity (version 6000.0.37f1 LTS) and integrates the Meta XR Interaction SDK, as well as OVR passthrough visualization.

Shared Spatial Anchor The software leverages *Unity's Shared Spatial Anchors (SSA) (v63)* [1] template for aligning the virtual scene with the physical environment [2]. The calibration phase utilizes a "Gizmo," a visual reference for the alignment of axes (X, Y, Z) with the physical space. This ensures precise positioning and alignment of the virtual objects within the physical environment Fig. 4. The calibration process is aided by the passthrough view on the HMD, providing a stable and intuitive reference surface. The use of this Gizmo enhances co-presence by ensuring that both users can consistently align virtual elements, even as they move within the physical space.

Multi-User Environment

The system utilizes Photon Unity Networking (PUN) for real-time synchronization between users, ensuring low-latency interaction and consistent 3D scene synchronization. The synchronization protocol is embedded within a custom script that utilizes Photon's "PhotonView" component, enabling scene elements to be shared between users in real-time [12] [3].

3.2.2 Hardware

The MR-CoCo testbed is deployed on the Meta Quest 3 devices, which display the MR scene. The devices are configured to operate in passthrough mode, allowing real-time integration of the physical and virtual worlds. While the system can run in standalone mode, for research purposes, the "Editor Mode" in Unity is used to facilitate debugging and monitoring of the application by the experiment moderator Fig. 4.

4 Experimental Design

This study represents an initial testing phase within the MR-CoCo testbed, which is designed for continuous research and iterative development. This section outlines the research questions, the experimental setup, the participant couples, the procedure, and the metrics. We selected the boat configuration because it represents a complex, highly customizable product. In contrast, simpler products typically do not require such advanced visualization tools, according to current industry practices. We aimed to evaluate the benefits of immersive configuration in contexts where traditional methods fall short due to product complexity.

[1] [https://github.com/oculus-samples/Unity-SharedSpatialAnchors

[2] https://developers.meta.com/horizon/documentation/unity/unity-spatial-anchors-overview/

[3] https://www.photonengine.com/pun

4.1 Research questions

We addressed the following research questions, divided into three categories:

RQ1: *Co-Located Collaboration:* Does co-located user collaboration affect interaction in MR environments?

RQ2: *Configuration - Couple Decision Making:* Does MR-CoCo improve decision-making during couple-based product configurations?

RQ3: *Usability:* How do users evaluate the usability of MR-CoCo according to the SUS scale?

4.2 Setup

The experiment was conducted in a dedicated meeting room, chosen to ensure sufficient physical space and minimize external interference. The room offered adequate lighting and acoustic conditions to support verbal communication between the couple. Its dimensions allowed comfortable side-by-side standing positions, crucial for co-located interaction and shared access to the physical table used as the spatial anchor.

A real table was positioned at the center of the room, serving as the physical reference for the SSA. This ensured the accurate alignment and stability of the virtual 3D sailboat model across both headsets. The use of a large, stable surface (minimum recommended size: 180 cm x 100 cm) contributed to enhancing co-presence, natural hand gestures, and ease of calibration during the setup phase.

MR-CoCo hardware setup is composed of two PCs used for the experiment are as follows:
PC A: Intel Core i7-7700H, 16 GB RAM, Nvidia GTX 1070 GPU.
PC B: Intel Core i7-13620H, 16 GB RAM, Nvidia RTX 4060 GPU.

And two Meta Quest 3 devices in passthrough mode to enable mixed visualization of the physical and virtual worlds, and two computers with different hardware specifications to support the MR devices Fig. 4.

Both PC were connected via the same Internet network, enabling real-time synchronization of virtual environments between the devices. Each PC is connected to MR devices via wired links for real-time debugging *"unity editor mode"*. This methodology helps research assistants when debugging during experiment scenes, allowing users within the virtual scene to resolve bugs or problems.

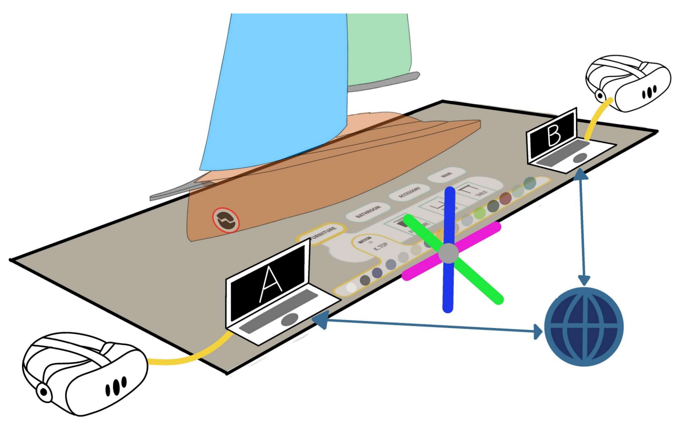

Fig. 4: **MR-CoCo Testbed Architecture:** Two PCs (A and B) and two HMD viewers are synchronised on the same network via the Photon PUN platform. The SSA is displayed directly on the actual table, allowing users to align the scene and ensuring a smooth and perfectly coordinated experience between the viewers displaying the synchronised scene.

4.3 Procedure

The experiment was approved by the institutional ethics committee. To evaluate the benefits of the MR-CoCo testbed, we conducted a user study through qualitative metrics. The experiment was performed in co-location collaboration with the simultaneous participation of two people. The devices were tested to minimize any physical discomfort associated with prolonged HMD use, ensuring a comfortable and safe

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experience. The research assistant introduced the experiment, monitored user interactions, took notes during the experiment, observed the couples' actions, and intervened if technical problems or interaction difficulties arose. The steps of the experiment are divided into the following steps Fig. 5.

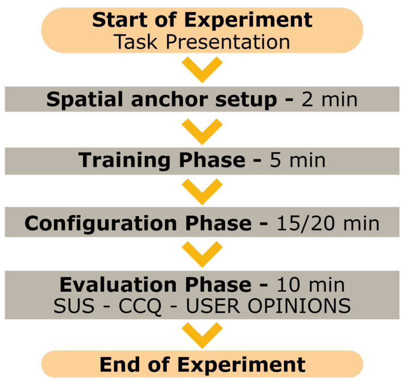

Fig. 5: **Procedure**: divided into 4 steps to be performed for the procedural task to be carried out correctly

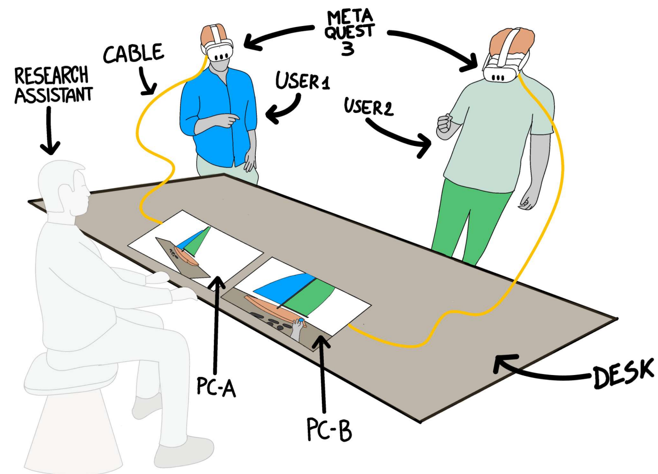

Fig. 6: **Experimental setup**: The research assistant (left) monitors from the PCs (A+B), the actions of each user as they interact with the sailboat model in MR. The couple is side-by-side as they complete the configuration task.

Task Presentation: The couples were briefly introduced to the task and asked to stand side-by-side Fig. 6, then they were asked to wear HMDs so that the research assistant could start the scene.

Spatial anchor setup phase: Each user calibrated the scene by positioning the "gizmo" at a predefined corner of the physical table, ensuring accurate alignment of virtual elements within the shared environment.

Training phase: During this phase, the couple familiarized themselves with the MR-CoCo interface and learned how to use the main configuration functions. Users first select the "cube" button and then choose the color that appears on the list, dragging it to the cube to change its color. After this step, when the couple understands how the UI works, they start the main experiment of the sailboat configuration.

Configuration phase: In this phase, the couple simulates a purchase scene and configures a sailboat to reflect mutual preferences by collaborating in MR, being in the same room, side-by-side Fig. 6. During the activity, users can view the product from all angles, ensuring a comprehensive understanding of its characteristics. Verbal communication between the couple is permitted, allowing open discussion on the operations.

Evaluation phase: Finally, each user completed separately the questionnaire to evaluate their configuration experience, focusing on elements such as system usability, level of collaboration, and perception of the MR environment. At the end of the experiment, the couple was asked to provide their feedback orally.

4.4 Couple Participants

Voluntary adult participants were recruited via a publicly available online form disseminated through social media platforms. Eligibility criteria included: (1) being at least 18 years of age, and (2) the ability to participate with another adult (a friend or colleague), as the study required dyadic participation. This approach was adopted to reduce communication barriers and foster spontaneous collaboration, aiming to ensure relational and communicative homogeneity within each couple. The final sample consisted of 48 participants (24 males, 24 females), aged between 20 and 40 years (M = 27.20, SD = 4.42), organized into 24 couples. Gender composition of the couple was balanced: 8 male-male, 8 female-female, and 8 mixed-gender couples. Participants were selected based on prior familiarity with technology. Among the 32 individual users (from the 24 couples) who reported experience with MR, 18 had previously used MR applications. Self-assessed MR proficiency was reported on a 7-point Likert scale (1 = novice, 7 = expert), yielding a mean score of 4.42 (SD = 2.03).

4.5 Metrics

Here, we describe the metrics collected to evaluate the testbed MR-CoCo.

Co-Presence Couple Questionnaire We used an enhanced co-presence configuration questionnaire (CCQ) featuring additional questions on configuration, couple decision-making, and collaboration, using a Likert scale (1 lower to 7 higher) [5].

This metric evaluates the degree of connection and synchronization the couple felt, focusing on mutual awareness, engagement, and the ability to interpret each other's nonverbal cues. The couple provided ratings ranging from partner presence and communication to evaluation of configuration choices, supporting the MR-CoCo application. **System Usability Scale - SUS** Each user of the couple compiles the SUS questionnaire separately [3]. We used the SUS questionnaire, which consists of 10 questions (Likert scale: 1 = strongly disagree, 5 = strongly agree). We then calculated the SUS value for each participant, ranging from 1 (poor) to 100 (best imaginable). **Couple Opinions** Finally, open-ended questions were administered to collect couples' qualitative impressions and suggestions about MR-CoCo.

5 Results

The MR-CoCo experiment lasted approximately 30 minutes per couple. However, two of the 24 couples did not complete the task, noting the difficulty of using MR. The findings from this user study provide key insights into the usability and collaborative dynamics of MR-CoCo. The results are structured around three key areas: Co-Presence Communication, Evaluation of Configuration, and Support for Collaboration.

5.1 Co-Presence Configuration Questionnaire Results

Co-Presence Communication in Couples The overall mean score for this category was 5.60 (SD = 0.23) Fig. 7.

Higher scores were observed in Harmony (A4) and Collaboration (A7), indicating strong co-presence and teamwork. Comparing the other categories the lowest score was in Usability (A6), suggesting challenges in the fluidity of interaction.

Configuration - Decision Making The overall mean score was 6.07 (SD = 0.20) Fig. 7.

The couples reported high agreement on the final configuration (B2) and positive evaluations of collaboration (B3). Some variability in (B3) suggests differences in preference for collaborative versus individual approaches.

No significant differences were analyzed based on couple composition (male-male, female-female, female-male). The focus remains on identifying common interaction patterns and collaborative dynamics.

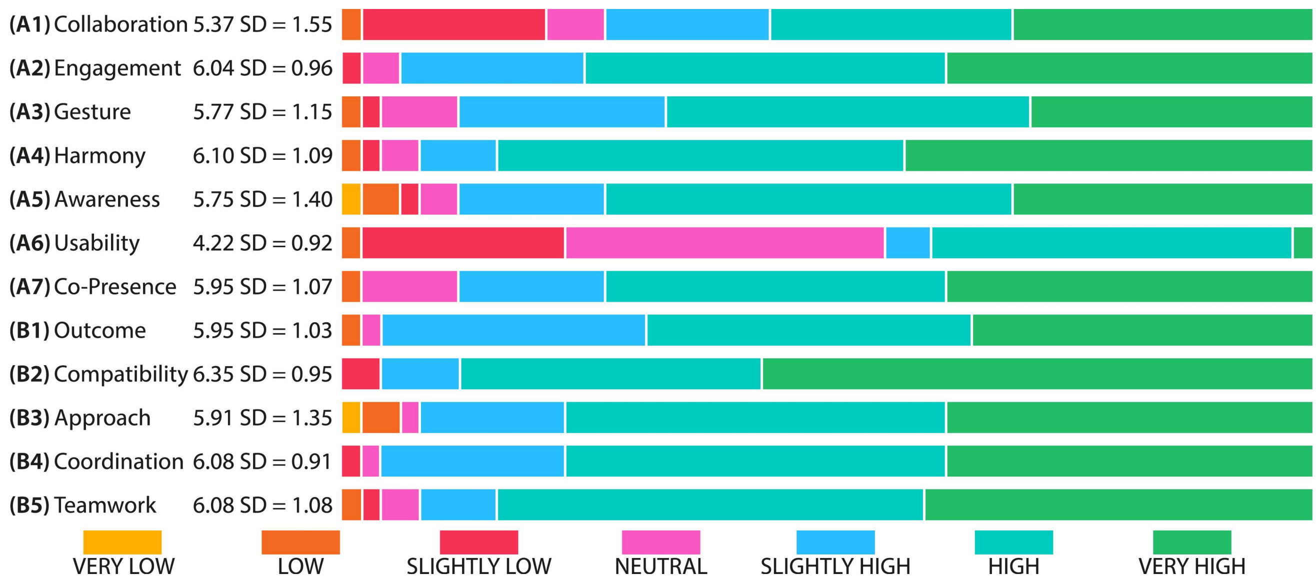

Fig. 7: **Co-Presence Configuration Questionnaire**: Matrix displaying the frequency of user responses, with categories ranging from very low to very high. On the left are the names of the analyzed category and the mean value.The distribution captures all user preferences within the minimum to maximum range.

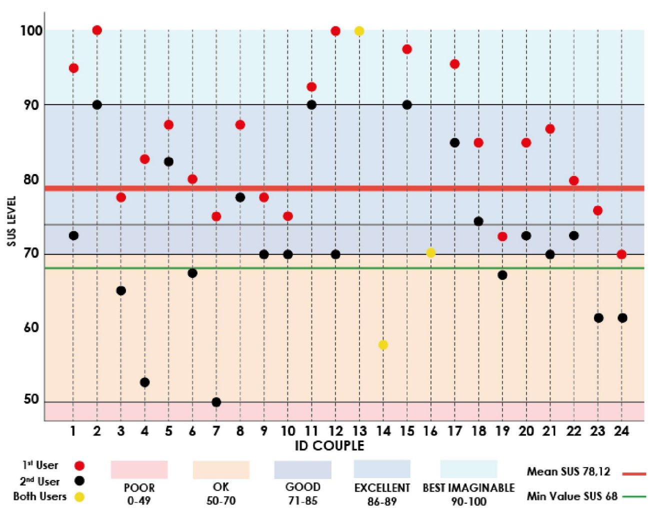

Fig. 8: **SUS results**: A score distribution plot showing the validation of the X-axis (0-100) and user couples on the Y-axis. Each column represents the individual usability scores for each couple member. A red LINE indicates the average SUS score, while a gray bar highlights the minimum score. Four colored sections represent the SUS rating categories: Excellent, Good, Acceptable, and Poor.

5.2 System Usability Scale (SUS) Results

The SUS results indicate that most users found MR-CoCo usable, with an average SUS score of 79.06 (SD = 14.32) Fig. 8. Only five users reported scores below the SUS average, indicating some difficulties in system usage.

The distribution of SUS scores is categorized as follows:

- **Best Imaginable** (SUS > 90)
- **Excellent** (SUS 86-89)
- **Good (SUS 71–85) - Obtained result**
- **Acceptable** (SUS 50–70)
- **Poor** (SUS < 49)

Two extreme outliers were observed: Couple 12 (SUS = 40) and Couple 3 (SUS = 95). The variation in scores suggests that users with less experience in MR faced initial usability challenges.

The red line in Fig. 8 represents the overall average SUS score, while the gray line indicates the minimum usability threshold. These results highlight the need for refining interface clarity and training processes to improve accessibility for all users.

6 Discussion

The results of this experiment contribute valuable insights for refining the system and informing future research directions. We divided this section into five subsections: CCQ and SUS findings, user opinions, limitations, and future works.

6.1 Co-presence Configuration

The results of the CCQ indicate that MR-CoCo effectively supports collaboration between couples. High scores in Harmony (A4) and Collaboration (A7) suggest that the couple felt a strong sense of connection and teamwork during the experiment. The ability to sense reactions and interpret gestures (A1, A3) further contributed to a positive interaction experience.

However, the lower rating in Usability (A6) indicates that the fluidity and naturalness of interaction were not optimal. This could be due to technological limitations, unfamiliarity with the system, or initial difficulties in coordinating actions. Addressing these factors could enhance the overall user experience.

In decision-making, the couple demonstrated a high level of agreement on the final configuration (B2) and were generally satisfied with the collaborative process (B3). The variability in responses to B3 suggests that while many found collaboration beneficial, some couples may have preferred working individually. Future iterations of MR-CoCo could explore adaptive mechanisms that accommodate different collaboration styles.

Regarding support and facilitation, MR-CoCo was rated highly in terms of coordination and teamwork (B4, B5), highlighting its effectiveness in structuring collaborative efforts.

6.2 System Usability

The SUS results indicate that MR-CoCo was generally well-received, with an average SUS score of 79.06, classifying it within the 'Good' usability range. However, the presence of five users with scores below the average suggests that usability challenges require further investigation.

The color-coded SUS categories in Fig. 8 reveal that most participants rated the system in the range (70-90), entering at least "good" (71-85) and "excellent" (86-89) scores. Only 3 users rated it as 100 (best imaginable), and one user rated it as 50 ("poor").

The variance in SUS scores highlights differences in user experience, particularly for those less familiar with MR environments. The two extreme outliers—Couple 12 (SUS = 40) and Couple 3 (SUS = 95)—suggest that while some participants found the system overall easy to use, others struggled with its interface and interaction design. One of the main issues identified was related to the "grabbable" functionality: when users did not perform the correct hand gesture (e.g., pinching) to interact with the color spheres, they were unable to apply changes to the product effectively. This led to some frustration, particularly among less experienced users. These users may have encountered difficulties due to unclear onboarding procedures, a complex navigation system, and challenges in adapting to MR interactions.

The lower-scoring users' feedback suggests a need for refinement in user training, gesture recognition, and the clarity of the interaction flow. Future iterations of MR-CoCo will focus on simplifying the onboarding process, improving gesture recognition accuracy, and providing clearer feedback during interactions to reduce the learning curve and improve usability for all users. Overall, the variance in SUS scores underscores the need for ongoing improvements in training, interface design, and system feedback mechanisms to streamline the user workflow and ensure a consistent experience across users with varying levels of familiarity with MR environments.

6.3 Couples' Opinions

Open-ended feedback from couples provided valuable insights into the strengths and limitations of MR-CoCo, offering key areas for improvement. Overall, users appreciated the system's ability to facilitate real-time collaboration, intuitive interaction, and immersive experiences. However, various challenges emerged related to cooperation, usability, interaction, visualization, and system limitations.

Cooperation and Communication One of the most frequently mentioned improvements was the ability to preview a partner's choice before applying it. This feature would enhance mutual awareness and coordination in shared decision-making. The feedback suggests that stronger visual cues and clearer communication channels could improve co-presence and facilitate smoother interactions between users.

Usability Enhancements Usability concerns focused on the need for a more flexible visualization system, additional customization options, and clearer feedback mechanisms. Users suggested the ability to manually rotate models for better inspection, expanding the available color and texture options, and integrating a zoom function for better visibility of small objects. Furthermore, couples requested a confirmation or review step at the end of the configuration process to solidify choices and enhance engagement.

Additionally, experienced sailboat users highlighted the importance of displaying key specifications such as length, anchor details, and tank capacity. While MR-CoCo was designed for collaborative configuration, incorporating relevant product data could enhance decision-making, especially for users familiar with technical specifications.

Interaction Refinements Qualitative feedback indicated challenges with hand tracking accuracy during color selection, highlighting a need for improved gesture precision and interface ergonomics. The couples also reported that identifying configurable elements was sometimes unclear, due to limited prior knowledge of sailboat components or unclear UI labels. Further refinements, such as contextual tooltips or interactive labels, could support user understanding.

Visualization and System Limitations Users noted discrepancies in graphic rendering quality due to variations in computer graphics hardware, highlighting a limitation that affects system consistency. Enhancing graphical optimization and standardizing visual fidelity across different hardware configurations would help mitigate these discrepancies.

Mobility restrictions due to the tethered setup were also noted, with some users expressing concerns about cable limitations. While necessary for observational purposes, exploring wireless or alternative tracking solutions could enhance user freedom and comfort.

Furthermore, participants' feedback revealed difficulties in identifying configurable elements, primarily due to unfamiliarity with nautical terminology. While button icons were designed to alleviate this issue, further refinements, such as interactive labels or contextual tooltips, could enhance clarity.

User Suggestions and Future Improvements User feedback also highlighted several suggestions for enhancing immersion and interaction. Some participants expressed interest in experiencing environmental elements, such as simulating the water level or the sailboat's actual dimensions, to enhance their spatial understanding. Others suggested an option to highlight configurable elements dynamically to streamline the interaction process.

Regarding training, participants recommended a structured sequence with numbered steps to provide clearer guidance. In addition, some users preferred an avatar representation of the partner in augmented mode rather than seeing them with the HMD. This preference suggests that integrating avatar-based representations could improve social presence and engagement in collaborative tasks.

The feedback from open-ended questions underscores the importance of refining MR-CoCo's usability, communication, and visualization features to enhance co-presence and collaborative decision-making. Addressing the identified challenges through improved interaction design, expanded customization options, and enhanced training processes will help streamline the interaction and increase confidence during decision-making. Future developments should focus on integrating these user-driven insights to optimize MR-CoCo for a broader and more diverse user base.

6.4 Limitations

Despite the positive outcomes of MR-CoCo, several limitations were identified that impact user experience and the overall system effectiveness:

Human Factors: Many users experienced difficulties with their initial interaction with MR, which affected their early experience. However, as training progressed, users became more familiar with the interface and interaction modes, resulting in more autonomous configuration and improved task execution. This led to a more comprehensive understanding of the system. Additionally, participants completed the task in an average of 15 minutes, faster than the expected 20-25 minutes.

The personal interpretation of the experience also varied, with factors such as communication dynamics between the couple, the distribution of control over configuration, and task responsibility influencing the outcome. An AI system capable of analyzing the conversation and tracking individual user movements could provide further insights into these behaviors.

Furthermore, the assistant's lack of awareness of the scene in MR posed limitations. Since the assistant was not integrated within the MR scene, they lacked precise spatial awareness of virtual object positions. Future iterations could benefit from including an in-scene observer or moderator, equipped with an HMD and pointing tools, to enhance guidance and coordination during the task.

Technical Issues: A significant issue during the experiment was the frustration caused by the limited cable connection to the HMD. Users felt restricted in their movements, which hindered their sense of immersion.

Additional technical challenges arose during the scene creation process. The mesh rendering limitation restricted the independent use of the HMD, requiring a direct connection to the PC for optimal performance. Moreover, the PUN system's synchronization limit of 1000 objects led to delays during object synchronization.

Another limitation was the inability to handle user occlusion. This prevented users from seeing the actions of others in the shared environment. Implementing avatars to represent users would improve the visibility of interactions and provide a more natural representation of each user's actions.

6.5 Future Works

Although the results obtained in this study are promising, the work primarily focuses on the interaction dynamics of co-located couples and collaborative behaviors. However, further analysis reveals that there is still room for improvement in the user interface to enhance the system's overall learnability. The testbed is designed to evolve through successive iterations, enabling the ongoing testing of new solutions and continuous refinement of the user experience based on empirical feedback.

Future developments should prioritize enhancing the initial training experience to accommodate varying levels of familiarity with MR. This could include the provision of step-by-step guidance on gesture interactions, interface navigation, and product customization. Additionally, incorporating visual feedback during interactions would be advantageous, as it would help clarify whether user actions are being correctly executed. Addressing the usability concerns observed in lower-scoring participants will be crucial to optimizing MR-CoCo for broader and more intuitive adoption.

While MR-CoCo was presented as a more immersive and collaborative alternative to traditional product configurators, this study is preliminary and lacks a comparison with a baseline system. Given that the combination of immersive, co-located, collaborative interactions in MR is a relatively novel approach, we were unable to identify a suitable baseline for a direct comparison. The primary objective of this study was to gather initial usability and interaction data within a shared MR environment.

To reduce perceived complexity, the sailboat's components were simplified. In the event of difficulties, users were interacting with the components could request assistance from the research assistant. For future case studies, we plan to adopt a simpler configuration to further improve user accessibility. MR-CoCo is intentionally designed to be flexible and easily reconfigurable, accommodating a variety of product types, industries, and collaborative scenarios.

To support this evaluation, standardized validation instruments will be employed, including the Game Experience Questionnaire (GEQ) by IJsselsteijn et al. [19], with a particular focus on the Social Presence module to assess interpersonal dynamics and user engagement in collaborative scenarios.

Further enhancements to MR-CoCo could include the integration of AI-driven virtual assistants, which would facilitate decision-making and further enhance the realism and personalization of the user experience. Additionally, incorporating user-specific avatars and expanding customization options will provide a more dynamic and immersive interaction.

Future research could explore the versatility of MR-CoCo across industries that require high levels of user customization, including automotive, architecture, and consumer electronics. Expanding the system to support more complex configurations, as well as incorporating features to handle occlusion and user presence, will further improve the collaborative experience, especially in remote settings. Moreover, refining the interface to reduce initial navigation challenges and enhancing the system's adaptability to diverse user needs will be key to broadening its applicability in real-world contexts.

7 Conclusion

This study presents MR-CoCo, a testbed designed to explore collaborative product configuration in MR environments. By integrating MR with real-time interaction and immersive visualization, MR-CoCo enhances collaborative decision-making, particularly in the context of configuring a luxury sailboat. The results demonstrate the system's ability to facilitate more engaging, fluid interactions, improving collaboration among users during configuration tasks.

MR-CoCo fills a gap in the literature by offering a novel MR-based collaborative product configurator. It supports real-time, synchronized interaction between co-located and remote users, fostering an immersive environment for product visualization. This approach not only enhances communication but also promotes greater user engagement and satisfaction compared to traditional, individual configuration tools.

The study highlights MR-CoCo's potential in facilitating mass personalization through immersive technologies. By enabling shared, collaborative decision-making, users reported increased confidence in their decisions and a more positive perception of the configured product. These findings underscore the benefits of MR environments, where synchronized interactions improve both user experience and satisfaction during the configuration process.

Usability testing, as indicated by the SUS, shows positive ratings, with users accepting the system despite initial challenges related to navigation and interface familiarity. This suggests that MR-CoCo can offer an intuitive platform for complex configuration tasks, with potential for further refinement.

In conclusion, MR-CoCo demonstrates the effectiveness of MR in enhancing collaborative product configuration. Its immersive interface not only promotes more informed decision-making but also fosters a satisfying user experience. Beyond its application in sailboat customization, MR-CoCo serves as a flexible testbed for investigating collaborative workflows, interface design, and decision-making dynamics in MR. Its modular architecture allows for adaptation to diverse industries, including automotive, architecture, and marine, positioning MR-CoCo as a valuable tool for future research on user-centric configuration systems. As a long-term testbed, it will continue to evolve, supporting ongoing innovation and refinement in collaborative MR applications.

Supplemental Materials

Open Testbed is available at `https://github.com/Vr3xMelab/MRCOCO-Testbed`, released under a CC BY 4.0 license, and they include: (1) video presentation of the MR-CoCo, (2) open source Unity material.

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