"Wizards vs Muggles!" — MOFA: A Game Framework Exploring the Design Space of Spontaneous Collocated Mixed Reality

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Figure 1: Actual gameplay screenshots from a third-person spectator view of our five spontaneous collocated mixed reality game prototypes using MOFA framework: (a) *The Duel* – Competitive play on the streets of SoHo, NYC; (b) *The Dragon* – Puppeteering Play at the Oculus Transportation Hub, NYC; (c) *The Ghost* – Asymmetric play inside a museum in Shenzhen; (d) *The Training* – Single-player play in a park under the bridge, Brooklyn; (e) *The Duck* – Collaborative play in a common area between office buildings in Shenzhen; (f) The final image represents the quick registration process for spontaneous collocation.

ABSTRACT

As Mixed Reality (MR) head-mounted displays (HMDs) become more prevalent, their use is shifting from private, controlled environments to spontaneous, public settings, reminiscent of scenarios from fantastic fiction. Everyday locales are thus transformed into potential gaming stages, a concept we term *Spontaneous Collocated Mixed Reality* (SCMR), which blurs the boundaries between designated play areas and the public sphere. Within SCMR, the inherent power imbalance between HMD wearers ("Wizards") and non-wearers ("Muggles") introduces complex challenges for mixed reality designers, such as social engagement, acceptance, and awkwardness. To explore this under-researched area, we conducted a formative study and adopted a Research through Design (RtD) approach, developing a game framework called *Multiplayer Omnipresent Fighting Arena* (MOFA), which facilitates rapid prototyping within the SCMR context. Over two years, our empirical studies of game prototypes using MOFA—*The Training*, *The Duel*, *The Duck*, *The Dragon*, and *The Ghost*—have revealed the design space of

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SCMR. Furthermore, we find that employing game design strategies guided by the design space, such as explainable interaction affordance, third-person speculation, role diversification, and device asymmetry, can address these social challenges and lead to more engaging, inclusive, and harmonious shared reality experiences in public spaces.

CCS CONCEPTS

• **Human-centered computing** → Interaction design theory, concepts and paradigms; **Mixed / augmented reality**; Collaborative and social computing systems and tools; Participatory design.

KEYWORDS

Augmented reality, Collaborative mixed reality, Social bodily play, Bystander inclusion, Game design, Spontaneous Collocated Mixed Reality

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1 INTRODUCTION

In recent years, the proliferation of see-through Mixed Reality (MR) head-mounted display (HMD) devices, such as Vision Pro [3] or Meta Quest 3 [6], has increased their prevalence in the consumer market. It's anticipated that more people will incorporate mixed reality into their everyday lives. Thanks to video or optical see-through technology [31], a Head-Mounted Display (HMD) wearer can see their surroundings and move around freely, expanding usage scenarios from private, controlled environments to public, spontaneous settings [11, 34]. However, introducing MR headsets into public and social spaces creates complex social challenges due to the inherent power imbalance between HMD wearers ("Wizards") and non-wearers ("Muggles") [14, 19, 45, 56]. These challenges include the impact on social experiences, privacy, and safety of non-wearers [18, 21, 45].

Although the Harry Potter series has deeply ingrained itself in modern society's collective consciousness over the past two decades [54], consider this: how would you react if a wizard duel, like those from Harry Potter, suddenly unfolded at a familiar public location like King's Cross Station in London, in real life? Introducing spontaneous, unusual play behavior in public settings can cause cognitive surprises and conflicts between players and bystanders [14]. Such scenarios could become a reality soon as consumer-level mixed reality headsets become more prevalent in public spheres. Despite much research on handheld augmented reality in public settings [8, 46, 47], and also much on collocated collaborative head-worn mixed reality in preset environments [9, 13, 17, 20, 25, 28, 38, 48, 51, 52, 61], there is limited literature on the design space of spontaneous collocated mixed reality games, which can permeate social and public spaces without prior setup. We believe that this scenario will become more common in the near future [34].

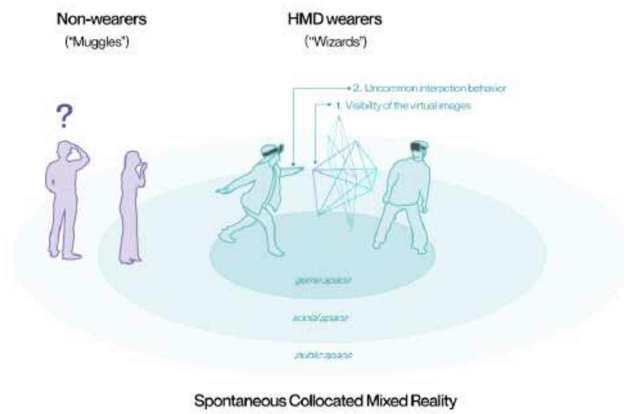


Figure 2: Spontaneous Collocated Mixed Reality

In this investigation, we introduce the concept of *Spontaneous Collocated Mixed Reality* (SCMR). We define SCMR as a scenario where at least one participant wears a HMD MR device in close physical proximity to others, whether they wear HMD or not, within a public and social space as determined by proxemics [26]. We illustrate this concept in Figure 2. SCMR differs from preset MR experiences due to its spontaneity. Each encounter is quick and temporary, not heavily dependent on preset technology such as pre-scanned areas [49], AR Cloud [22, 60], WiFi routers, cellular networks, or even internet connections, which may not always be available.

Given that MR HMDs are designed to only augment the wearers' view, the inherent challenges of SCMR primarily arise from imbalanced power dynamics between HMD wearers and non-wearers, as well as unpredictable social environments in the field. In designing SCMR games, it's crucial for designers to consider not only the gameplay between wearers but also the involvement of bystanders, including spectators aware of the game, active participants, and even passersby who choose not to engage in the game, as their intentions may vary. Additionally, the challenge for game designers could be even greater. Unlike traditional screen-based AR game design, such as Pokemon Go [46], the design of play within SCMR is more akin to social bodily exertion games [23, 33, 40] or sports design [41], which are theoretically grounded in concepts of inter corporeality and intentionality from phenomenology [37, 44, 50]. To sum up, the design space of SCMR remains largely unexplored, posing complex challenges for game designers.

To open up the design space of SCMR, we first began with a formative study which involved a literature review in HCI and then preliminary interviews with 20 participants. The participants ranged from junior, senior, and expert exertion gamers to game designers, HCI researchers, and cognitive researchers. Our objective was to identify the main challenges and potential design opportunities within SCMR. As described in Section 3, this included understanding issues related to intention differentiation, device distinction, and their effects on public, social, and private spaces.

Then we adopted a Research through Design (RtD) methodology [24] to dive deeper into the SCMR design space by creating the

SCMR prototyping games and getting feedback from actual user tests. To quickly explore within this SCMR context, we developed *Multiplayer Omnipresent Fighting Arena* (MOFA), an open-source game framework for rapid prototyping of various SCMR games. MOFA facilitates the exploration of spontaneous collocating technologies, intuitive interactions, game rules, modalities of play, and spatial utilization, among other elements.

Over two years, through iterative and additive design and empirical studies of five MOFA game prototypes – *The Training*, *The Duel*, *The Duck*, *The Dragon*, and *The Ghost* – we have delineated the SCMR design space. Our findings reveal that strategies such as leveraging explainable social interaction affordances, non-wearer experience design, device asymmetry, and role diversification can mitigate social challenges, thus fostering engaging, inclusive, and harmonious shared reality experiences in public arenas.

Finally, we conducted quantitative studies with 24 participants to assess engagement, emotional responses, and physical activity during gameplay. Through quantitative surveys, we gathered data on aspects such as social awkwardness, acceptance, engagement, and movement metrics, including steps taken and calories burned. These studies were designed to reinforce our understanding of the SCMR design space, focusing on promoting socially harmonious, inclusive, and engaging gameplay experiences.

The contributions of this paper are as followed:

- MOFA, an open-source game framework, facilitates quick prototyping of SCMR games. It's specifically designed for SCMR and includes features like role assignment, cross-device support, and asymmetric play. Additionally, it simplifies network object synchronization and spontaneous collocating registration.
- A comprehensive game design space in SCMR, developed from user studies across five game prototypes. This design space guides MR game designers in creating experiences that are engaging, inclusive, and conducive to social harmony in public spaces.
- Key takeaways and game suggestions for future SCMR game designers, based on insights from our exploration

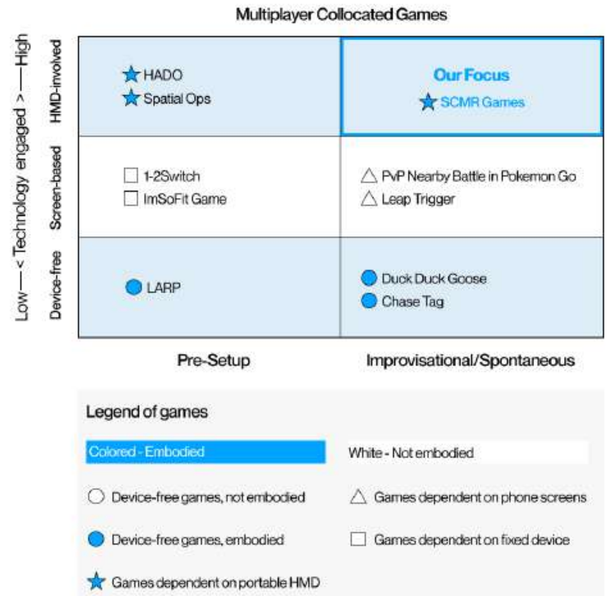


Figure 3: Multiplayer Collocated Games

2 RELATED WORKS

2.1 Intercorporeal Collocated Play

Unlike traditional location-based multiplayer AR experiences, such as Pokémon Go [8, 46, 47, 55], or collocated handheld AR games [57, 59], in SCMR, HMD wearer naturally uses their body as a controller for the game, highlighting the need for designs that promote social inter-bodily engagement [40]. Therefore, the game design in SCMR is fundamentally rooted in social bodily play [42, 43].

Previous HCI research has delved into various forms of social bodily play. Live Action Role Play (LARP), for instance, highlights non-digital, physically and socially engaging play. It's defined by physical enactment, improvisation, and direct participant interaction, without an external audience [35]. Transitioning to digital contexts, fixed screen games like 1-2-switch [1] link physical activity with digital entertainment, pushing players to engage physically with the game. This blending of physical exertion with digital gameplay is further elaborated in the ImSoFit framework, which outlines the future of fixed screen physical play game development [36].

While much research has been conducted on collocated AR and VR interactions [13, 17, 20, 25, 28, 38, 48, 51, 52, 61], there are only a few collocated see-through multiplayer head-worn MR games. Notably, games like HADO [9] and Spatial Ops [5] bring the concept of physical play into immersive MR environments. However, these games often require specific setups or pre-defined environments. This underlines the need for more spontaneous and adaptable MR experiences that can adjust to various public settings without extensive pre-configuration.

The conceptual frameworks of proxemics [15] and f-formations [12] significantly inform the exploration of social bodily play by offering insights into how spatial and social arrangements enhance interaction within shared physical spaces. These principles are instrumental in designing SCMR experiences that are socially engaging and spatially harmonious.

Research on the benefits of social play in exertion games [33] further supports the SCMR framework by underscoring the importance of multiplayer experiences and social interaction in enhancing game adherence and enjoyment. This body of work collectively informs the design space of SCMR, emphasizing the integration of physical activity, social interaction, and immersive digital content in creating engaging and harmonious public play experiences.

2.2 Collocated Mixed Reality Technologies

In order to achieve collocated mixed reality experiences, two fundamental problems need to be solved: network connection and coordinate registration. Network connection enables data transfer between devices to implement real-time synchronized display and interaction. Coordinate registration is crucial because multiple devices have to register their coordinate system to a shared space to display the same virtual content on top of the same physical location. Several methods have been developed to address these two challenges.

Collocated mixed reality experiences typically rely on two types of networking connections: a local network via a router as an intermediary, or the internet. However, access to both routers and internet connectivity is not always guaranteed. The pre-scanning method [30, 39, 49, 58] involves capturing the environment's point cloud, allowing devices to relocalize within a predefined spatial map. Although effective in creating a shared spatial reference, it requires extensive preparation and may not adapt well to dynamic environments.

The image marker technique uses an external image, which is tracked by devices to reset their coordinate system origins to the same spot. This method offers simplicity but relies heavily on the presence and visibility of the marker.

AR Cloud [22, 60] combines GPS and a Visual Positioning System (VPS) for initial and precise localization, respectively, allowing devices to share a global coordinate system. While it's a promising solution for collocated mixed reality, the AR Cloud infrastructure is still underdeveloped, limiting its availability in most places.

These techniques, while advancing collocated mixed reality experiences, underscore the need for spontaneous, low-preparation methods adaptable to diverse and changing environments.

3 DESIGN SPACE OF SPONTANEOUS COLLOCATED MIXED REALITY

Our investigation began with initial interviews as the first part of our formative study to identify the key dimensions of design space and challenges of SCMR. We engaged with a diverse group (N=20) of experts across the fields of augmented reality, game design, and HCI research. These conversations helped us to identify early on the multifaceted nature of SCMR and its potential impacts on both MR device wearers and non-wearers.

3.1 Definition of SCMR

Spontaneous Collocated Mixed Reality (SCMR) emerges when at least one participant, equipped with a Head-Mounted Display (HMD) mixed reality device, is in close physical proximity to others, regardless of their device use. Central to SCMR is its integration into both social and public spaces, grounded in the principles of Proxemics of Human Territory [26, 27], as shown in Figure 2. In this context, social space is characterized as the sphere within which spontaneous social interactions occur among individuals, fostering a sense of community and shared experiences. In contrast, public space expands this domain to include those nearby but not directly involved in MR activities, such as passersby and potential observers, thereby broadening the MR experience's reach into the wider public arena. Distinct from traditional MR setups, SCMR is defined by its spontaneity, emerging without the need for preset setups or schedules. This spontaneity ensures that each SCMR encounter is quick and temporary, influenced by the immediate context and the participants involved. It is this unique aspect that allows SCMR to transform everyday spaces into immersive, interactive arenas that blend the digital with the physical, engaging both active participants and the wider community in new and unexpected ways.

3.2 Early Identification of Challenges

Defining the challenges of SCMR requires an understanding of its dynamics and impact on both Wizards ("wearers") and Muggles("non-wearers"). This imbalanced power of engagement underscores the essence of SCMR, promoting a spectrum of interaction possibilities (need References if have). The preliminary phase of our investigation involved conducting semi-structured interviews with experts spanning game design, and HCI research. These interviews, complemented by a literature review, shed light on the multifaceted nature of SCMR.

The initial interviews revealed several key dimensions of SCMR challenges.

(DC1) **Device and User Differentiation**: Within SCMR environments, differentiation between devices and users leads to power imbalances and asymmetric relationships between wearers and non-wearers. This affects perceptions of presence, engagement, and brings up concerns regarding privacy, consent, and the ethical use of public spaces.

(DC2) **Social Acceptance and Awkwardness**: The challenge of social acceptance and the potential for social awkwardness emerged as critical considerations. The public's reception of SCMR activities can vary widely, from curiosity and interest to misunderstanding and discomfort. This variability underscores the need for SCMR experiences to be designed to minimize awkwardness and foster a positive, inclusive atmosphere for participants, bystanders, and passersby.

(DC3) **Intention Differentiation**: The diverse motivations and expectations of Wizards and Muggles add complexity to SCMR. Whether for entertainment, socialization, or exploration, the intentions driving engagement in SCMR scenarios significantly influence the design and deployment of these technologies.

(DC4) **Social Bodily Play**: This concept presents an additional layer of challenge compared to screen-based AR. It necessitates the design of experiences that inherently involve the wearer's body as an interaction medium in SCMR. Consequently, game design in SCMR must consider social affordance to establish a cognitive intercorporeality flow.

By synthesizing insights from expert interviews and literature, our formative assessment served as a starting point in defining the early challenges of SCMR. It underscored the necessity of addressing inherent power imbalances, social dynamics, and the diverse intentions that characterize spontaneous mixed-reality interactions in public settings. This formative assessment sets the stage for exploring the intrinsic characteristics and challenges of SCMR, guiding future research and development efforts in creating socially inclusive, engaging, and harmonious MR experiences.

3.3 Intrinsic Characteristics of SCMR

The essence of SCMR lies in its intrinsic characteristics, which fundamentally shape the dynamics of interaction within public spaces. These characteristics highlight the unique aspects of SCMR that differentiate it from other forms of digital and physical interaction, offering new opportunities and challenges for game design and public engagement.

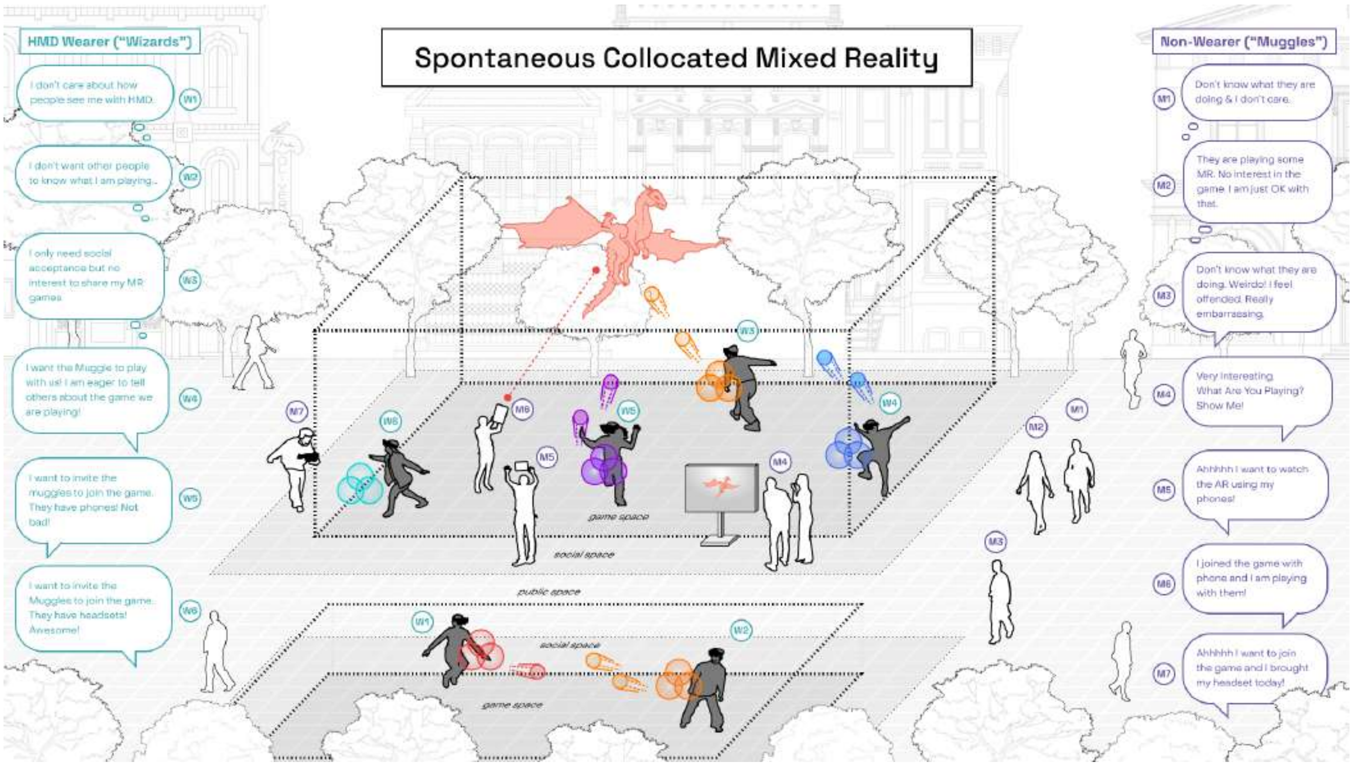


Figure 4: Intention Differentiation of People in SCMR space

The introduction of SCMR naturally engenders a power imbalance between device wearers and non-wearers [14]. We propose a cross-user and cross-device dual-axis framework categorizing user experiences based on device immersion and user engagement. The Y-axis represents a spectrum of devices ranging from immersive to less immersive: head-mounted display stereoscopic augmented reality (StAR) devices, Handheld Augmented Reality (HAR) devices, Fixed Augmented Reality (FAR) devices, and scenarios with No device. The X-axis classifies user roles from voluntary to involuntary engagement: Players, Bystanders, and Passersby, culminating in a matrix that encompasses 12 distinct user types.

3.3.1 *Cross-device categorization.*

- (D1) **StAR Devices**: StAR devices provide an immersive experience to players through the utilization of head-tracking and motion tracking to accurately track the position and orientation of the player's head in real time. This data is then used to generate a first-person view (FPV) that corresponds to the concept of an egocentric view.
- (D2) **HAR Devices**: HAR devices supports both FPV and TPV gaming experiences. HAR devices allow players to observe the physical world un-augmented, while also providing the capability to observe the augmented scene on the screen. The device is held by the player, thus separating the device's movement from the player's head movement.
- (D3) **FAR Devices**: Fixed Augmented Reality (FAR) devices are anchored to specific physical environments, integrating them into the user's field of vision through stationary screens or installations. These devices offer a communal form of engagement, where multiple participants can share in the augmented experience simultaneously, albeit from a fixed perspective.
- (D4) **No Device**: Incorporating "No Device" into our framework acknowledges the significance of traditional, un-augmented play and interaction within SCMR environments. This category serves to highlight the importance of considering individuals in the vicinity of SCMR activities who are not equipped with any digital augmentation devices yet remain integral to the social and interactive fabric of the space.

3.3.2 *Cross-user categorization.*

- (U1) **Players**: Players are actively engaged participants who interact directly with the MR environment. Whether through StAR, HAR, FAR, or no device, players are characterized by their volitional involvement in the gameplay, exerting control, and making decisions that influence the game's outcome.
- (U2) **Bystanders**: Bystanders are individuals who observe the MR gameplay without actively participating. This role is crucial in contexts where the MR experience is shared or public, as bystanders can significantly contribute to the social ambiance and collective experience. Design considerations for

bystanders include providing meaningful ways to understand and potentially influence the gameplay or narrative from a non-participatory stance.

(U3) **Passersby**: Passersby are those who encounter the MR experience incidentally, without prior intent to participate or observe. This role highlights the permeability of MR experiences to the broader social and physical environment.

3.3.3 Intention Differentiation. Intention Differentiation within SCMR illustrates the varying objectives and levels of engagement desired by both HMD wearers and non-wearers. This diversity in intentions shapes the dynamics of social presence and engagement in public spaces, presenting unique design challenges and opportunities for inclusive and engaging SCMR experiences.

We summarize 6 intentions in different levels for HMD wearer and non-wearer from our early formative assessment.

Six levels of inclusion of HMD wearer

(W1) **Unconcerned Players**: Those who are indifferent to public perception while wearing HMDs, focusing solely on their immersive experience without regard to external views.

(W2) **Privacy-Conscious Players**: "Wizards" who prefer to keep their gameplay private, avoiding drawing attention. They seek discreet engagement, minimizing external observation and interaction.

(W3) **Acceptance without Sharing**: "Wizards" desire social acceptance in public spaces but choose not to share their MR experiences, maintaining a boundary around their engagement.

(W4) **Eager Sharers**: Enthusiastic about their MR experiences, these Wizards are keen to share with non-wearers, aiming to demystify MR activities and foster interest.

(W5) **Casual Inviters**: Open to spontaneously including non-wearers with smartphones, these Wizards aim to broaden their play space to incorporate nearby participants.

(W6) **Enthusiastic Recruiters**: The most inclusive group, actively inviting non-wearers with headsets into their MR realm, seeking to expand their interactive experiences through shared technology.

Seven levels of inclusion of non-wearers

(M1) **Indifferent Passersby**: Individuals who may not notice or express interest in MR activities, remain indifferent to the experiences unfolding around them.

(M2) **Tolerant Observers**: Aware of MR activities without engagement desire, accepting MR games in public spaces as part of public activity diversity.

(M3) **Disturbed Onlookers**: Those uncomfortable or offended by public MR activities, viewing them as intrusive or awkward, highlighting SCMR's potential to disrupt public norms.

(M4) **Curious Spectators**: Non-wearers interested in MR activities, willing to learn more and possibly observe closely, serving as a potential bridge for MR community engagement.

(M5) **Included Spectators**: Individuals eager to observe MR activities through smartphones, showing interest in the visual aspects of the experience.

(M6) **Ready-to-Join with HAR**: Muggles interested in participating with smartphone access, eager yet feeling limited by their device capabilities.

(M7) **Ready-to-Join with StAR**: Non-wearers interested and equipped with necessary headset technology, fully prepared and enthusiastic about joining the MR experience.

3.3.4 Spontaneous game space in public setting. In the realm of SCMR, any public space possesses the potential to be seamlessly transformed into an immersive game environment without the need for prior permission from individuals in the public domain. This spontaneous transformative process is profoundly shaped by the principles of proxemics [26], the study of human spatial behavior, offering critical insights for designing SCMR experiences that both respect and enrich social and public interactions.

(S1) **Game Space**: The game space constitutes the core digital environment where the MR gameplay occurs. It is a virtual arena that seamlessly overlays or interweaves with the physical environment, crafting a blended reality where digital and physical elements coexist and interact. This space is defined by the boundaries of the game's mechanics, rules, and narrative, dictating how players can interact with the game and, by extension, with each other and the surrounding environment. The game space's design must consider how it overlays the physical world, ensuring that interactions within this digital domain enhance rather than detract from the immersive experience of both wearers and non-wearers.

(S2) **Social Space**: The social space within SCMR acts as an essential intermediary, connecting players and bystanders. By incorporating principles of proxemics, this space should be crafted to enable spectatorship and interaction that feel natural and maintain respectful social distances. It becomes an area where the digital narrative expands into the communal domain, inviting bystanders to engage at a comfort-respecting level. This setup allows MR experiences to be observed, shared, and possibly joined by those within the proxemic social territory, thereby enhancing inclusiveness and community involvement in the MR experience.

(S3) **Public Space**: Public space acts as the canvas for SCMR experiences, highlighting the essential need for thoughtful and respectful integration of digital content within the physical public realm. Guided by proxemic considerations, the deployment of MR experiences in these settings should aim to complement, not disrupt, the existing social and functional dynamics. Achieving a balance between gameplay and the broader context of public life—from parks and streets to intimate home gatherings—requires a nuanced understanding of the proxemic expectations of all individuals present. The goal is to design SCMR experiences that resonate with public spaces, enhancing social interactions without imposing on those not actively participating, thereby fostering a sense of community and shared public connection.

3.4 Intrinsic Challenges of SCMR

The integration of SCMR into public spaces, while offering new avenues for interaction and engagement, introduces a set of intrinsic challenges. These challenges center around social acceptance, social

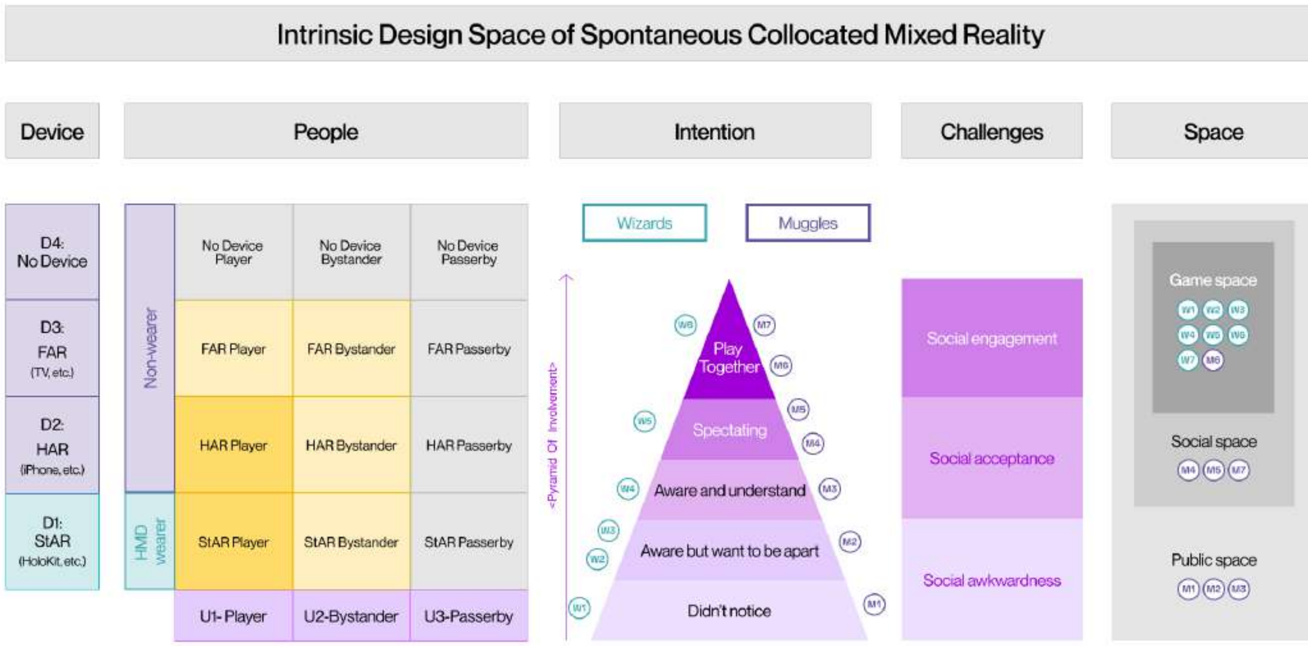


Figure 5: Intrinsic Design Space of SCMR

awkwardness, and social engagement, each playing a crucial role in the successful adoption and harmonious existence of SCMR in public life. Addressing these challenges is paramount for designers and researchers aiming to create socially inclusive, engaging, and harmonious MR experiences.

(C1) **Social acceptance**: Social acceptance of SCMR hinges on the broader public's reception of MR activities in shared spaces. This acceptance is influenced by several factors, including the perceived value of MR experiences, their impact on public space utility, and the degree to which they respect privacy and social norms. A key challenge lies in designing SCMR experiences that are seen as enhancing rather than intruding on public life, fostering a sense of community inclusion rather than exclusion. Achieving social acceptance requires careful consideration of the visibility and inclusivity of MR experiences.

(C2) **Social awkwardness**: Social awkwardness arises from the potential interplay between participants engaged in an SCMR experience and those uninvolved bystanders or passersby. This challenge is characterized by the confusion or discomfort that may occur when the social and virtual identities and embodiment of the players are conflicted or misunderstood. Strategies may include integrating explanations, affordances, narratives, and cues within the MR experience that help contextualize the activity for the public, thereby reducing the likelihood of misunderstandings or negative social reactions.

(C3) **Social engagement**: The challenge of social engagement within SCMR focuses on fostering meaningful interactions among all participants, including both MR users and the broader public. Engagement goes beyond mere participation, seeking to create a sense of involvement and contribution among those in the vicinity of the MR experience. This involves designing MR activities that encourage interaction and collaboration between users and non-users, leveraging the unique capabilities of MR to bridge the digital and physical worlds in ways that are inviting and compelling for everyone involved.

3.5 Summary

In this section, we provide an initial analysis of the intrinsic characteristics of SCMR to explore the design space, laying the groundwork for creating actual SCMR games. These insights also inform the development of a framework aimed at rapid prototyping of SCMR games, facilitating further investigation into this emergent field.

4 MOFA FRAMEWORK

To streamline our Research Through Design journey, we plan to abstract and modularize common elements across games into a flexible framework, rather than creating games within SCMR one by one. We will iteratively develop *Multiplayer Omnipresent Fighting Arena* (MOFA), an open-source framework designed to meet these criteria. This framework encourages rapid prototyping of various

SCMR games and allows for quick iterations based on user feedback and design modifications. To achieve spontaneity in SCMR environments, we have identified six key design requirements:

(R1) **Spontaneous Local Networking**: A system for fast, low-latency local device connection without relying on the internet connection or local Wi-Fi networks.
(R2) **Ease of Coordinate Registration**: A fast mechanism for synchronizing coordinates across devices, which eliminates the need for pre-scanning the physical environment and allows for seamless spectator participation.
(R3) **Auto Synchronization of Virtual Objects with Support for Asymmetric Gameplay**: A system to synchronize gameplay data consistently across devices, ensuring all participants view the same virtual elements while still supporting asymmetric elements.
(R4) **Compatibility with Handheld and Headworn Devices**: A framework that supports both handheld and headworn devices.
(R5) **Intuitive Interaction without Physical Contact**: Utilize the motion sensors of the Apple Watch to capture wrist movements for spell casting. This approach enhances remote attacking gameplay without necessitating physical contact between players.
(R6) **Quantitative Measurement**: The integration with iPhone and Apple Watch measures the player's movement distance, step count, and caloric expenditure, providing metrics of physical engagement.

4.1 Spontaneous Local Networking

For achieving spontaneity in SCMR, unlike preset MR, we can't rely on the internet connection, which might not always be available or it might suffer from high latency. We also can't assume that a low latency Wi-Fi router, allowing interconnection on the internal network, is always available.

We utilized Apple's MultipeerConnectivity framework [4] to establish a local network for co-located devices without relying on internet access or local routers. This framework facilitates rapid joining of nearby participants using various devices and ensures low latency data transfer for an immersive experience. The technology, which also underpins iPhone AirDrop, supports high-bandwidth low-latency data transfer via Bluetooth and Wi-Fi, eliminating the need for internet access. As a result, devices can communicate in a variety of environments, virtually anywhere.

Devices advertise their presence or browse for others during the connection setup. A browsing device sends an invitation upon discovering an advertising device, which can be accepted or declined. Once connected, devices can communicate with all others in the network. The MultipeerConnectivity framework maintains a round-trip time of roughly 30 ms, ensuring a seamless SCMR game experience.

4.2 Ease of Coordinate Registration

In SCMR aligning all players' AR coordinates is critical to ensure virtual objects are consistently placed at the same location across all devices. Traditional re-localization solutions, like external markers [32], markerless point-cloud pre-scanning [49], and Visual Positioning Systems [22], often fall short in spontaneous settings due to their complex setup and time consumption.

Hu et al. introduced a method called *InstantCopresence* [29] for coordinate registration. This method uses a dynamic marker image, like a QR code displayed on a phone, to align the origin of all connected devices. By using Apple ARKit's image tracking, the marker's position and rotation are communicated in real-time across devices. This real-time information exchange allows for the calculation of the host's coordinate origin in the client's space, using the least squares method as detailed in Appendix A. Consequently, the client device can reset its coordinate origin to match the host's, ensuring the same virtual object appears in the same physical location across all devices.

The accuracy of registration is confirmed visually. A virtual frame around the host indicates successful registration, while any misalignment means recalibration is required. The user flow of InstantCopresence is illustrated in Figure 6.

4.3 Auto Synchronization of Virtual Objects with Support for Asymmetric Gameplay

Ensuring real-time synchronization of virtual objects across all devices is crucial for a consistent SCMR game experience. This includes displaying and interacting with these objects with low latency. A robust and flexible networking system is required to synchronize the dynamic coordinates of player poses and virtual objects. It's also needed to support asymmetric gameplay dynamics.

We used the Unity game engine along with Netcode for GameObjects [7] as the multiplayer networking SDK. This allows seamless object and game logic synchronization in a host-client architecture. The host device holds authority over the game state, with changes distributed to all clients. Netcode for GameObjects offers a transport layer API, and we integrated Apple's MultipeerConnectivity for local network communication as an open source software as well. This networking SDK also permits asymmetric gameplay. Unique client IDs and hashes for networked game objects enable targeted transmission of exclusive data, giving varied perspectives and interactions.

4.4 Compatibility with Handheld and Headworn Devices

To permit bystanders with phones to participate in the SCMR game, which necessitates cross-device communication within SCMR, the MOFA framework supports not only HAR devices like iPhones and iPads, but also HMD StAR devices. For our StAR prototype device, we've chosen the HoloKit X [2].

The HoloKit X turns an iPhone into a mixed reality headset with stereoscopic capabilities, powered by iOS applications developed using the HoloKit Unity SDK. It accommodates both handheld and headworn devices, facilitating shared mixed-reality experiences. The iOS app developed for prototyping offers two rendering modes: monoscopic and stereoscopic. The app functions like typical screen-based AR apps in monoscopic mode. In stereoscopic mode, it projects a stereoscopic viewport on the phone's screen. When paired with the HoloKit X headset, this display is projected into the

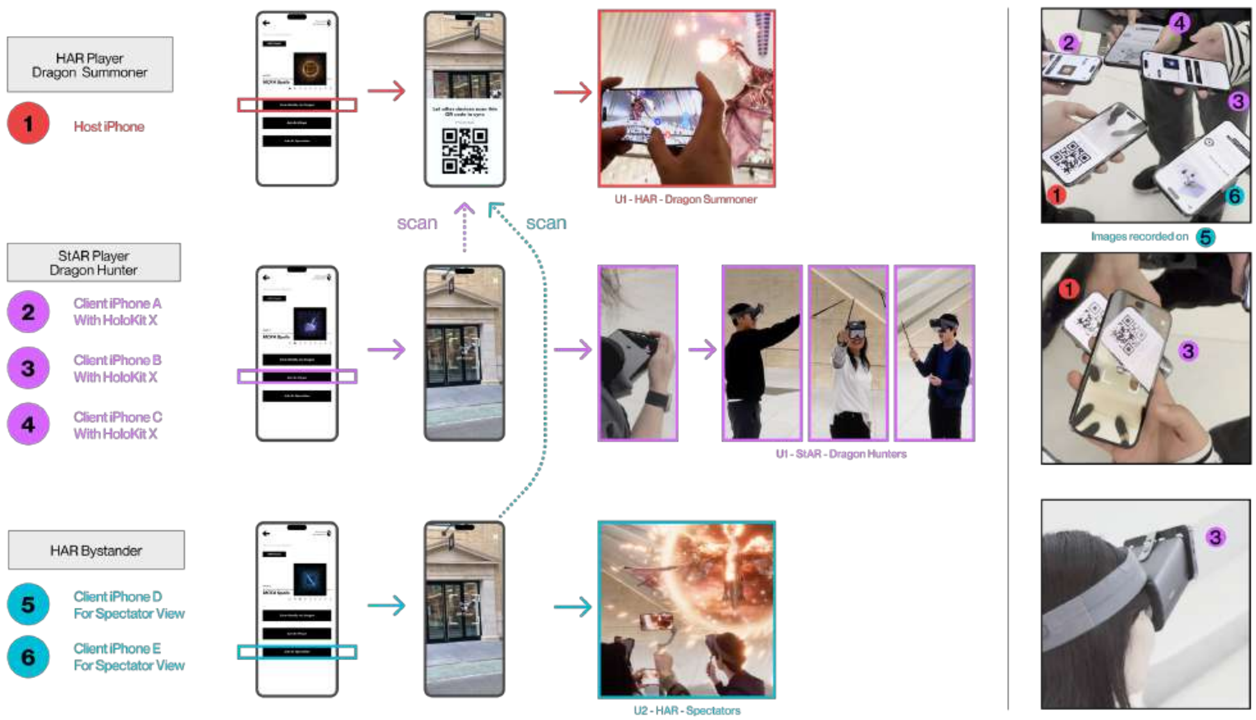


Figure 6: User flow for connecting client phones with host phones for spontaneous, quick and temporary multiplayer SCMR game experience

user's field of vision through semi-transparent glass, along with the real world.

This dual-mode functionality enables an iPhone to switch between handheld and headworn modes, streamlining the development process with a single Unity iOS application for varying device types. Moreover, this setup incorporates a Spectator View feature, which facilitates real-time streaming of multiplayer mixed reality experiences from a handheld device, thereby allowing bystanders to join the shared mixed reality experience.

4.5 Intuitive Interaction without Physical Contact

To develop a framework that is flexible enough for various types of SCMR gaming scenarios, we need to solve several problems.

4.5.1 Without Physical Contact. Many existing mixed reality systems can't detect physical contact between players. Thus, tangible interactions such as melee attacks are not recommended in game design. MOFA, a fighting arena, circumvents this issue. Here, players cast magic spells for intangible interaction with opponents.

To prevent the repetitive task of rebuilding the spell-casting system for each prototype game, a reusable spell-casting and magic spell system is incorporated into the MOFA framework. This makes magic spells accessible for all prototypes. The system includes a series of spell classes, each featuring a basic attack spell and a utility spell. Players can choose one magic class per game round. While basic attack spells have minor variations such as speed and size, utility spells differ, adding to the game's versatility. These can involve generating a shield or summoning a magic circle.

4.5.2 Explainable Embodied Interaction. Inspired by the magic spell-casting actions in Harry Potter, we've used the Apple Watch as a gesture control device to provide an intuitive interaction experience for players in MOFA. The Apple Watch's motion sensor detects the angle and acceleration of the user's hand, enabling natural spell-casting gestures. Players can swing their arms for a basic attack spell, or point their hands to the ground for three seconds and swing to cast a utility spell. For an enhanced experience, using a physical wand is highly recommended as it provides better affordance and explainability.

4.5.3 Affordance of Target. MOFA is an intangible spell-casting game, similar to a first-person shooter. It requires designing targets for players to attack. Since we can't physically harm the opponents in mixed reality, we'll instead create a magic shield in front of each player. This shield doubles as a destructible target and an indicator of the opponent's health status. By providing players with a clear target, we encourage focused corporeal interaction between players. When a spell strikes the shield, it fragments, creating a satisfying confirmation of impact for the attacker.

4.5.4 Quantitative Measurement. The Apple Watch allows us to collect data such as movement distance and calories burned while the player is engaged. This quantitative data, combined with user feedback, enhances our Research Through Design approach.

5 RESEARCH THROUGH GAME DESIGN

5.1 Overview of the Process

In order to gain a deeper understanding of the challenges within the design space of SCMR, we adopted a Research through Design (RtD) approach [24]. This included the creation of actual SCMR game prototypes and gathering feedback through user tests. Over a span of two years, we developed five game prototypes: *The Training*, *The Duel*, *The Duck*, *The Dragon*, and *The Ghost*. These were inspired by a magical world akin to Harry Potter, where muggles and wizards coexist.

Our research on SCMR using the MOFA framework included nearly 300 game tests and interviews across four continents - the United States, China, Australia, and Germany. We engaged with various cultures in diverse settings such as universities, streets, parks, shopping centers, and train stations. Our participants comprised experts, developers, students, and novices from various fields, providing a wealth of feedback.

The following RtD description will include quotes from the semi-structured interviews conducted after the game tests. Through these prototypes, we explored design aspects like device asymmetry, interaction affordances, and inclusion, while also addressing social challenges and boosting public engagement. This international, multidisciplinary effort underscores the potential of SCMR to encourage engaging, inclusive, and harmonious experiences in public spaces, setting the stage for future SCMR game developments.

5.2 The Training: A Single-player Play

Our exploration starts with the single-player game design "The Training", a game where players engage in magical duels with the cartoon character. This prototype aims to explore and develop the basic interaction module of MOFA. The game explores three interaction methods:

Hand-Gesture Interaction: Players cast spells through hand gestures.

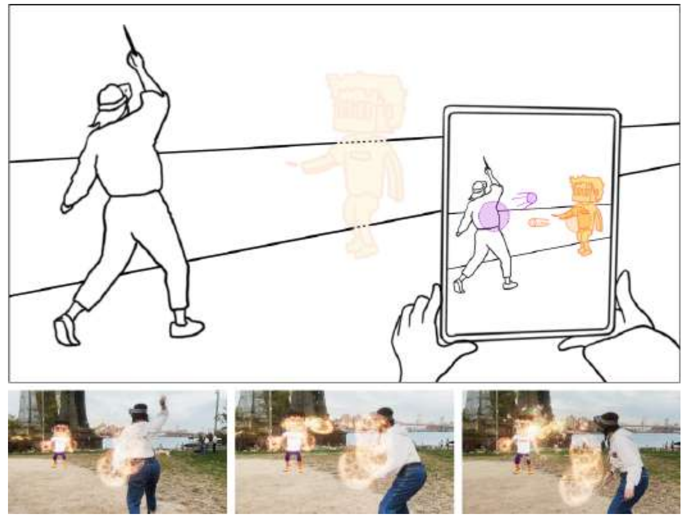
Apple Watch Interaction: This method leverages the Apple Watch's acceleration tracking, allowing players to cast spells with hand movements.

Apple Watch & Wand Interaction: Combining the Apple Watch's tracking capabilities with a physical wand enhances the spell-casting experience, offering an affordance to magic casting.

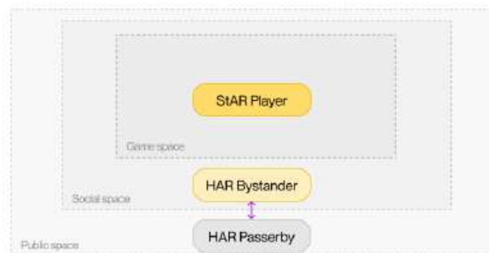
5.2.1 Expectation. Our expectation for this game is that the *"wave-to-cast"* magical experience will facilitate a quick grasp of AR interactions, enabling players to easily understand and engage with the game mechanics.

5.2.2 Observation. Among our interaction methods, the Apple Watch + wand combo emerged as the most effective, striking the right balance between responsiveness and immersive feedback. Key observations include:

Enhanced Feedback with Apple Watch: The precision of gesture recognition on the iPhone proved insufficient, with the Apple Watch offering a more reliable alternative for detecting movement. Most



(a) Designed and actual game plays



(b) Game design configuration in SCMR design space

Participant	Device	View	Role	Information	Action
Player 1	StAR	First-Person	Wizard	Full	Attack

(c) Game design configuration

Figure 7: The Training

participants cast their spells after the initial prompt: *"Think of yourself as a wizard, now use your wand."*

Wand as a Physical Affordance: The wand significantly reduced the interaction learning curve, intuitively guiding players on how to cast spells.

Identity and Story Through the Wand: Players attributed a strong sense of identity and narrative to the wand, enhancing their immersion and engagement. One girl remarked, *"If you take away the wand, I don't know who I am anymore. And no one knows what I'm doing,"* after her wand was taken away during the test.

Public Engagement: The visual spectacle of players waving wands captivated bystanders, drawing attention to the game even without visible AR elements. Pedestrians, especially children, would stop and watch the gameplay.

5.2.3 Unexpected Observations. Social Sharing: Observers enthusiastically recorded gameplay, despite being unable to capture the

AR content. They also expressed a stronger willingness to share recordings with AR content included.

Replayability Concerns: Despite positive feedback on the fun factor, players were hesitant about replaying the game in public settings, citing social awkwardness as a significant barrier.

Limited Movement: Players tended to remain stationary, focusing more on hand movements than on utilizing the entire play space for dodging and moving.

5.2.4 Future Steps. Responding to these insights, we propose several design improvements:

Spectator View: To bridge the gap between HMD wearers and bystanders, a spectator view could allow onlookers to see the AR action, fostering social sharing and reducing awkwardness.

Multiplayer mode: Introducing battles between players could enhance engagement and replay value, encouraging friends to enjoy the magical duels together.

5.3 The Duel: A Competitive Play

Following the exploration in "The Training," we continue to develop a multiplayer battle mode titled "The Duel." This iteration was designed to enrich the experience by upgrading player-versus-player magical combat and enabling bystander spectator view through HAR devices. This development is supported by user studies focusing on the spectator experience, revealing the multifaceted impact of this feature. The game explores: (a) two-player vs. single-player dynamics; (b) integrating spectator mode.

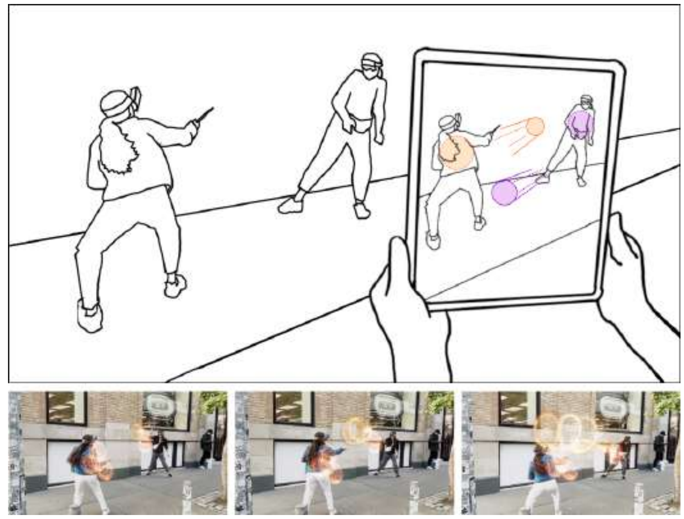
5.3.1 Expectation. "The Duel" aims to replicate the captivating magical battles seen in popular films, elevating player engagement and replayability while reducing feelings of awkwardness. The introduction of a spectator mode is expected to foster social acceptance and engagement, further mitigating any sense of awkwardness by involving bystanders in the gameplay narrative.

5.3.2 Observation. The game has received significant popularity, with almost all players exclaiming, *"It's so much fun!"* This is evident in the following aspects:

Replay Value: Transitioning to multiplayer combat significantly increases the game's replayability, with players more inclined to participate in numerous rounds, demonstrating enhanced enjoyment and engagement. In the single-player training mode, most players do not engage in a second round. However, in the Duel mode, almost everyone plays at least two rounds.

Intensity and Movement: The multiplayer mode encourages dynamic movement, contrasting with the stationary nature observed in single-player gameplay. The MOFA framework enables us to record the distance covered, with significantly greater distances in two-player games compared to single-player games. The real-world chase and dodge elements significantly increase the game's immersion.

Spectator Involvement: The spectator view enhances the sense of involvement for both HMD wearers and non-wearing players. HMD wearers themselves have expressed that they feel more immersed after receiving timely feedback from spectators. Many players and spectators have requested their own videos for sharing. Participants reported a stronger sense of social acceptance, stating, *"I don't feel awkward at all playing in front of other classmates. I think they would be envious of me."*



(a) Designed and actual game plays

(b) Game design configuration in SCMR design space

Participant	Device	View	Role	Information	Action
Player 1	StAR	First-Person	Wizard	Full	Attack
Player 2	StAR	First-Person	Wizard	Full	Attack

(c) Game design configuration

Figure 8: The Duel

Social Engagement: The game fosters a deeper sense of social connection among players, distinguishing itself from purely virtual games by emphasizing physical presence and interaction. *"I enjoy playing with friends in person. It's different from online battles,"* said one interviewee. Players express a preference for competing alongside friends in tangible spaces, underlining the value of real-world social interactions.

Less Social Awkwardness: Playing AR alone is awkward, but with two people, it's fun. Both HMD wearers and non-wearing players are more inclined to recommend the Duel over the Training mode. Responses from players include: *"playing alone feels a bit awkward,"* and *"I would never play alone on the street. But if someone accompanied me for a duel, I would play."*

Wand as an Explainable Affordance: The presence of the wand has been shown to vary in impact based on spectator visibility. When AR elements are not visible to onlookers, the wand significantly reduces feelings of awkwardness and enhances the overall enjoyment of the gameplay for both participants and spectators.

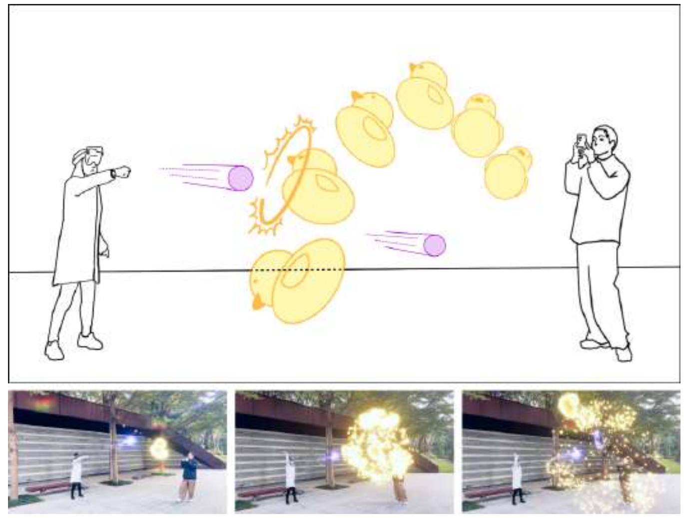
UI Design Challenges: Players found shields more intuitive than traditional health bars, prompting a redesign for better visibility and understanding during combat. We realized that during the dynamic combat process, players' attention was highly focused on their opponent's body, leading them to overlook other UI elements, especially those not centrally positioned in their field of view. Health bars distract players' attention, resulting in less cognitive flow. We also implemented a full-screen red effect when players were hit and added a crisp sound effect when the shield shattered, to make them more intuitively understandable.

Embodiment Feedback: Precise tracking and responsive interaction are paramount for maintaining player immersion. Any misalignment between player actions and game feedback, particularly concerning shield positioning and attack responsiveness, has been identified as a critical detractor from the overall experience, emphasizing the need for accurate embodiment feedback.

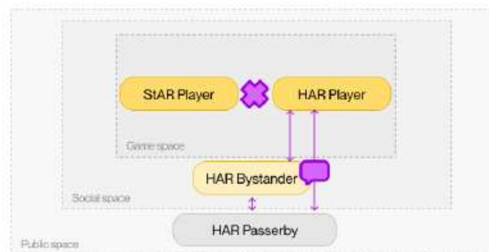
5.3.3 Future Steps. Building on these insights, future developments will explore:

Expand Multiplayer Experiences: Encouraged by the positive reception to *The Duel*, we plan to explore diverse multiplayer modes, recognizing their potential to alleviate social awkwardness and enhance engagement.

Integrate Active Participation for Non-Wearers: Investigating ways for smartphone-holding spectators to transition from passive observers to active participants could further enrich the SCMR experience, fostering a more inclusive and dynamic gaming environment.



(a) Designed and actual game plays



(b) Game design configuration in SCMR design space

Participant	Device	View	Role	Information	Action
Player 2	StAR	First-Person	Duck Hunter	Full	Attack
Player 1	HAR	First-Person	Slingshotter	Full	Throw

(c) Game design configuration

Figure 9: The Duck

5.4 The Duck: A Cooperative Play

We continue to develop *The Duck*, to explore the dynamic interactions between Head-Mounted Display (HMD) wearers and Handheld Augmented Reality (HAR) players. This game is inspired by classic games like Nintendo's "Duck Hunt" and the traditional sport of waterfowl hunting. In *The Duck*, gameplay diverges into two distinct roles: The "slingshoter" (HAR Player): Utilizes a smartphone or tablet to launch virtual ducks into the air by sliding their finger up on the touchscreen; The "duck hunter" (StAR Player): Wearing a head-mounted device, the player acts as the attacker, aiming to predict and intercept the ducks' flight path with magic balls. The game explores the asymmetric dynamics between StAR players and HAR players.

5.4.1 Expectation. We anticipated that "The Duck" would foster a competitive yet enjoyable MR experience, bringing HMD wearers and smartphone users together in a shared game space.

5.4.2 Observation. Our observations revealed critical areas for improvement:

Contrary to expectations, players found the game to lack depth and challenges. Unlike video games, the physical world is not able to offer a changing and well-designed environment for the gameplay. The static nature of gameplay—whereby the attacker could easily anticipate and hit targets—resulted in a monotonous experience that failed to sustain interest.

In contrast to The Duel, the embodied interaction of the other players is not predictable and is a very good source of the game flow, performing as the game target and giving an immediate response. However, the Duck doesn't properly utilize the player and opponent's embodied movement and reaction in this game flow.

5.4.3 Future Steps. In response to these insights, our future direction involves rethinking the design of asymmetrical MR experiences:

Redefining Asymmetrical Interactions: We aim to explore new ways to design asymmetrical gameplay that fully leverages the strengths of both StAR and HAR devices, ensuring that both players and spectators find value and excitement in the experience.

Enhancing Game Flow through Embodiment: Acknowledging that the unpredictability and embodiment of player movements are key to sustaining game flow, we plan to incorporate elements that better utilize physical space and player dynamics. This could involve designing gameplay that encourages more movement and strategy, increasing the challenge and variability of each session.

5.5 The Dragon: A Puppeteering Play

Learning from the lesson of the duck, *The Dragon* introduces a new interaction paradigm. In this setup, HAR players, dubbed 'puppeteers,' take control of a majestic dragon with their mobile iPhone. Meanwhile, players equipped with StAR devices find themselves as dragon-hunting warriors, casting spells to battle the dragon. This design leverages the advantages of HAR devices, including:

Intuitive Control and Precision: HAR devices act as controllers, providing puppeteers with precise input capabilities that translate into fluid, dynamic control over the dragon's movements.

Third-Person Embodiment for Enhanced Mobility: The third-person perspective afforded by HAR devices liberates puppeteers from physical constraints, offering free movement. The asymmetric capabilities between the dragon and the hunters introduce a layer of complexity and excitement.

5.5.1 Expectation. We anticipate that this game will accommodate a larger number of players, providing them with a heightened sense of engagement. Previous games had a maximum of two participants, while "The Dragon" allows for an unlimited number of players in a single session.

Non-wearers can now control the dragon using their smartphones, finally being able to actively participate in the game interaction. We aim for this structure to balance power dynamics within the MR space, facilitating better connectivity between HMD wearers and non-wearers.

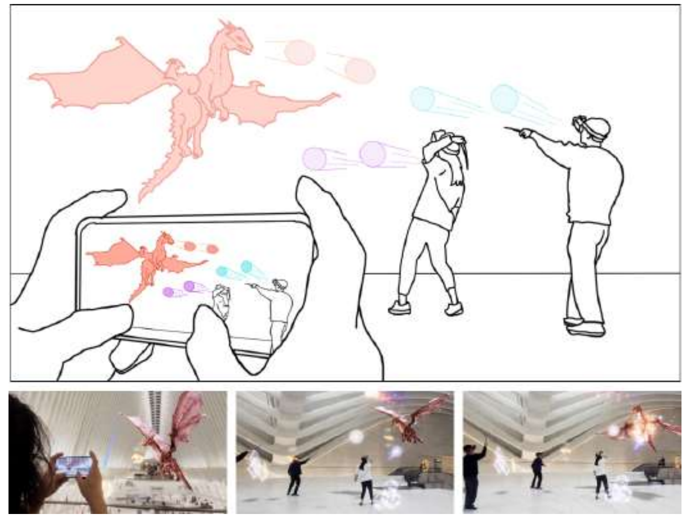
5.5.2 Observation. Key observations from "The Dragon" include:

Enhanced Immersion and Flow: The fusion of engaging narrative and physical interactivity elevates immersion across all player roles. The tangible interaction with the dragon introduces a continuous gameplay flow, making the story and game appealing to everyone.

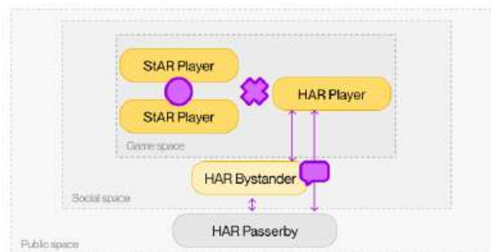
Increased Social Engagement: The asymmetrical AR design boosts social interactions among players, making the gameplay more intriguing. Players showed a keen interest in adopting the dragon role, expressing, *"This sparks more interest, and I would like to be the dragon, controlling those with HMDs."*

Collective Enjoyment: The game's capacity for multiple players amplifies its entertainment value, particularly suited for social gatherings. *"More players make it more enjoyable."* Participants commented, *"It's perfect for social gatherings like parties and provides great opportunities for social interaction."* The cooperative aspect and witnessing spells cast by allies contribute to a genuine team battle experience. *"When I saw different spells cast by my teammates shooting from behind me, I truly felt the sense of team battles in the game."*

Physical Activity and Space Requirements: Engaging in *The Dragon* entails considerable physical movement, necessitating a larger play area. *"This is a workout!"* and *"It's challenging to play interactive games like 'The Dragon' that involve significant physical movements in small spaces like homes or apartments. You need to go to a park."*



(a) Designed and actual game plays



(b) Game design configuration in SCMR design space

Participant	Device	View	Role	Information	Action
Player 1	StAR	First-Person	Dragon Hunter	Partial	Attack
Player 2	StAR	First-Person	Dragon Hunter	Partial	Attack
Player 3	HAR	Third-Person	Puppeteer (Dragon Summoner)	Full	Maneuver & Attack

(c) Game design configuration

Figure 10: The Dragon

5.5.3 Future Steps. Encouraged by the success of *The Dragon*, future directions include:

Expansion of Asymmetric Multiplayer Experiences: Inspired by the puppeteer mode's reception, we aim to develop more asymmetric MR games, diversifying the interaction models between HMD wearers and non-wearers.

Explore More Cooperative Gameplay Mode: Feedback has shown a preference for cooperative. We plan to explore game mechanics that promote asymmetric cooperation, enhancing the shared experience among players.

5.6 The Ghost: An Asymmetric Play

Building on the success of *The Dragon*, *The Ghost* introduces a collaborative and strategic gameplay design that enhances cooperation among players using different devices. Drawing on the iconic *Ghostbusters* film for inspiration, this game employs a unique partial information design strategy, engaging a StAR player as *"the ghost-buster"*, a HAR player as the *"detector"*, and another HAR player taking on the role of the elusive *"ghost"*, the *"ghost puppeteer"*.

The *"detector"*, equipped with HAR technology, is capable of revealing the ghost by firing a detection wave, while the *"ghost-buster"*—once the ghost is made visible—aims to subdue it with magic calls. This unique setup demands swift collaboration between players wielding different devices to defeat the ghost before it can claim victory. This game explores the dynamics of asymmetrical cooperation between StAR and HAR players.

5.6.1 Expectation. *"The Ghost"* aims to foster a rich cooperative experience, bridging HMD wearers and non-wearers through shared objectives and strategic interaction. This collaborative design is intended to enhance player communication, teamwork, and the collective devising of strategies to navigate the challenges within the game. By promoting collaborative problem-solving, players can capitalize on their distinct abilities and devices, deepening the gameplay's complexity and enjoyment.

5.6.2 Observation. Our observations revealed several noteworthy aspects:

Heightened Realism and Interactivity: Players reported a compelling sense of presence within the game world, actively engaging with the virtual threats and expressing genuine reactions to the ghost's movements. *"I genuinely felt that presence,"* one player commented. *"I was constantly running away from the ghosts. It exhausted me."*

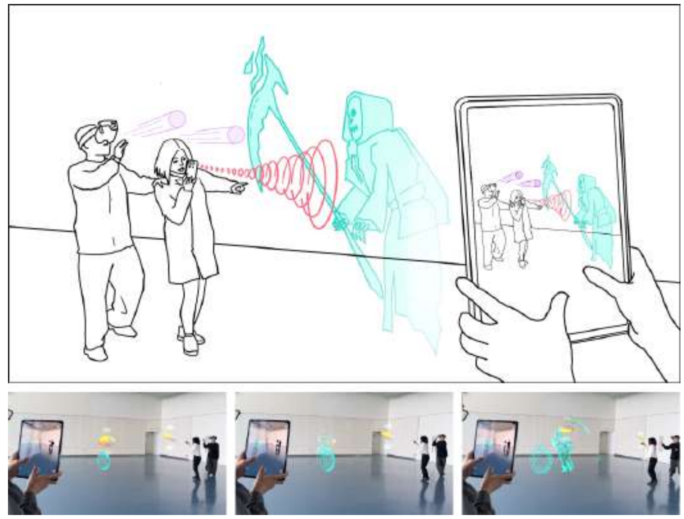
Challenges in Cooperative Gameplay: While the game's cooperative nature was designed to enhance the experience, a lack of clear cooperative signals sometimes led to confusion and diminished the overall gameplay quality. *"I didn't know where the ghosts were, and it felt a bit chaotic,"* one player mentioned.

Preference for Cooperative Over Competitive Play: Players displayed a strong preference for collaborative gameplay, highlighting the enjoyment derived from working together as opposed to engaging in direct competition. *"Then we can laugh and playfully interact with each other,"* one player described their experience.

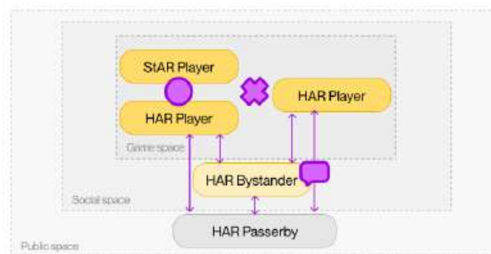
Asymmetrical Gameplay Intrigue: Many observers expressed interest in assuming the role of the ghost, highlighting the appeal of the game's asymmetrical design. Most bystanders gather around the controller of the ghost, eagerly anticipating what will happen next.

5.6.3 Future Steps. Moving forward, *"The Ghost"* sets the stage for further exploration into asymmetrical multiplayer designs in mixed reality:

Diversifying Asymmetrical Multiplayer Experiences: Motivated by the positive reception of the puppeteer mode in *The Dragon*, and now the collaborative dynamics in *The Ghost*, we are keen on expanding our portfolio of asymmetric MR games that encourage new interactions and teamwork strategies cross users and devices.



(a) Designed and actual game plays



(b) Game design configuration in SCMR design space

Participant	Device	View	Role	Information	Action
Player 1	HAR	First-Person	Detector	Partial	Detect
Player 2	StAR	First-Person	Ghostbuster	Partial	Attack
Player 3	HAR	Third-Person	Puppeteer (Ghost Summoner)	Full	Maneuver & Attack

(c) Game design configuration

Figure 11: MOFA - The Ghost

Incorporating Cooperative Gameplay Elements: The strong player interest in cooperative gameplay highlights the potential for developing games that focus more on asymmetric cooperation between HMD wearers and non-wearers, fostering a sense of unity and shared accomplishment.

6 USER EXPERIENCE STUDY

6.1 Study Design

Upon completing the final iteration of our five prototyping games, we conducted user studies with 24 participants. These participants, comprised of 8 females and 16 males aged 19 to 21, included students

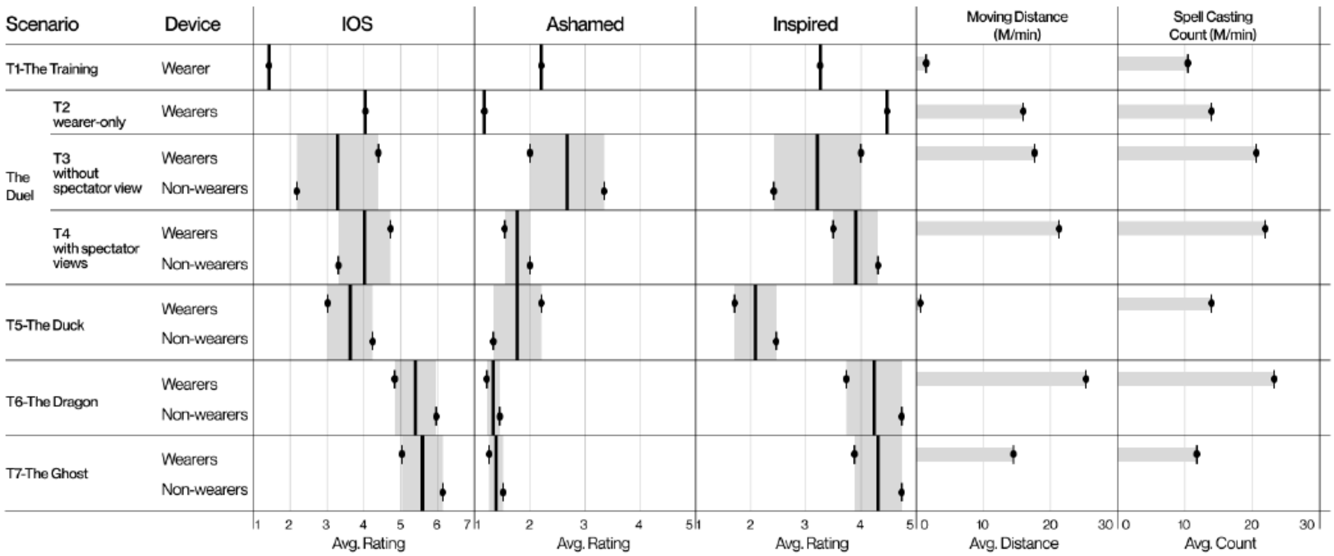


Figure 12: Graphical results of Likert scale and physical movements from user experience test

and game designers. The studies aimed to evaluate social awkwardness, acceptance, engagement, and physical activity, which included physical moving distance and spell casting count.

The study took place in common areas of the university, such as a large hall and four small seminar rooms, to minimize experimental interference. We conducted both surveys and interviews to gather quantitative and qualitative data. However, our primary focus in these studies was on collecting quantitative data to derive more concrete insights from the perspectives of both players and bystanders.

Participants were divided into two groups of 12, each undergoing identical experimental procedures.

We conducted 7 experiment scenarios as follows:

(T1) 4 StAR players played *The Training* individually in separate rooms.
(T2) 2 pairs of StAR players played *The Duel*, each in different rooms.
(T3) 2 pairs of StAR players played *The Duel* in a single room, observed by 8 non-wearers without spectator view.
(T4) 2 pairs of StAR players played *The Duel* in a single room, observed by 8 non-wearers with spectator view.
(T5) 4 pairs of StAR and HAR players played *The Duck* in a single room, observed by 4 non-wearers with spectator view.
(T6) 4 StAR players and 1 HAR player played *The Dragon* in a single room, observed by 7 non-wearers with spectator view.
(T7) 4 StAR players and 3 HAR players played *The Ghost* in a single room, observed by 5 non-wearers with spectator view.

6.2 Study Objectives

Our primary goal was to explore the concept that collective involvement enhances enjoyment and engagement, reinforcing the notion that shared experiences transform dreams into reality.

- Objective for Experiment Scenario T1-T4: Assess the impact of single versus multiplayer mode on gameplay experience; compare gaming experiences of both the HMD wearers and non-wearers without and with the spectator view of game content.
- Objective for Experiment Scenario T4-T7: Evaluate the comparative experiences of the five games from both the HMD wearers' and non-wearers' perspectives.

6.3 Measurement Metrics

We employed a within-subject design method for the game experience testing.

Emotion Measurement:

We utilized the Inclusion of Other in the Self Scale to assess perceptions of closeness and connectedness on a 1-7 scale. [10]. Additionally, we employed a set of negative and positive emotion scales, "ashamed" and "inspired" from the I-PANAS to measure social awkwardness and engagement [53], with participants rating their emotions on a 5-point scale.

Movement Measurement:

Data on running distance and spell casting count were collected to reflect physical activity as an indicator of engagement and excitement. To ensure comparability across games of varying durations, measurements were standardized to values per minute (/minutes).

6.4 Results and Discussions

Our user study results provide insightful findings into the SCMR experiences across various game scenarios.

(F1) Wearers reported feeling a greater sense of connection in scenarios where they interacted with other players (T2-T4) as opposed to playing alone (T1). Notably, cooperative game modes (T6 and T7) demonstrated higher Inclusion of Self in Others (IOS) scores than competitive gameplay (T4).

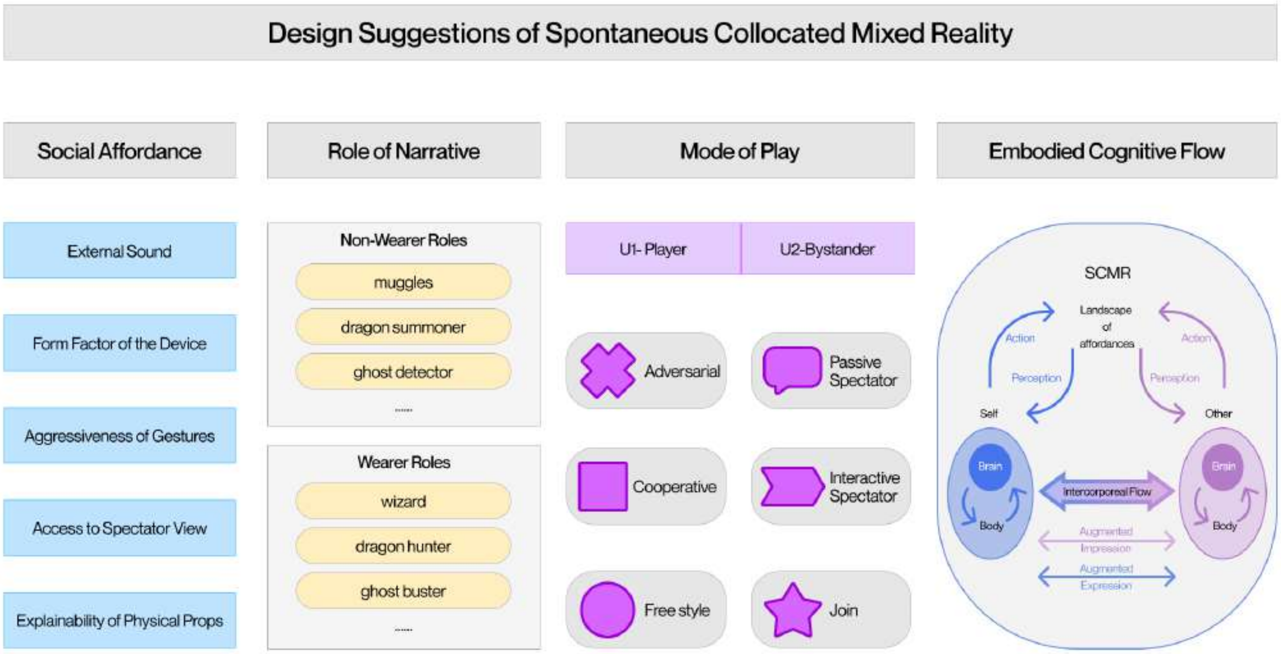


Figure 13: Design Suggestions for SCMR

(F2) Non-wearing participants reported a notable increase in connectedness when provided with spectator views (T4), underscoring the significance of inclusivity in shared experiences.

(F3) A wide emotional range was observed. Both HMD wearers and non-wearers experienced less embarrassment (Ashamed) in multiplayer scenarios with spectator views (T4-T7), suggesting that strategies that involve more people in the game increase social comfort.

(F4) A positive correlation was found between moving distance (M/min) and high inspiration levels (Inspired), suggesting that game scenarios that encourage physical movement (T4, T6, T7) tend to inspire participants more.

(F5) Spell casting frequency (M/min) was in line with moving distances, with more physically active games like The Duel, The Dragon, and The Ghost leading to increased spell-casting activity.

These findings highlight the strategic inclusion of non-wearers to minimize embarrassment. Using game design strategies, such as explainable social affordance, third-person speculation, role diversification, and device asymmetry, can address social challenges. This approach leads to more engaging, inclusive, and harmonious shared reality experiences in public spaces.

> "A dream you dream alone is only a dream. A dream you dream together is reality." — Yoko Ono

7 DISCUSSIONS, LIMITATIONS AND FUTURE WORKS

7.1 Takeaways and Design Suggestions

We have organized our design suggestions as depicted in Figure 13 and explain them as follows.

7.1.1 Explainable social affordance. The introduction of HMD wearers into public spaces often creates a disconnect between their social and virtual identities, potentially causing social awkwardness. Our studies emphasize the significance of using physical and explainable affordances, such as wands in *The Duel*, to bridge this gap by offering a tangible connection to the player's in-game persona. These affordances also help to lower the learning curve for players. Furthermore, incorporating additional elements like loud music, costumes, and visual cues can enrich the gaming experience and enable clearer communication of player behaviors to the public.

7.1.2 Role of narrative. Narrative plays a crucial role in SCMR gameplay, fostering deeper connections among players and between players and non-players. Through compelling storytelling, such as the dynamic between the dragon hunter and dragon summoner, narratives significantly enhance gameplay immersion. In *The Duel*, the distinction between wizards and muggles aids non-wearers in understanding the gameplay mechanics, thereby increasing their desire to participate and transition from spectators to active players.

7.1.3 Mode of play. Asymmetric gameplay introduces a compelling layer of complexity and strategy, arising from power imbalances between different player roles. Designing for asymmetric play—whether competitive or collaborative—promotes innovative strategies and transitions in gameplay. For example, in *The Dragon*, HAR puppeteers have more freedom of movement compared to HMD wearers. Likewise, in *The Ghost*, disparities in information access among players present unique challenges and opportunities for strategic gameplay.

7.1.4 Embodied Cognitive flow. The core excitement of MR gaming stems from its reliance on embodied cognitive flow [16], where physical interaction with the game environment is crucial. We observed that the failure of *The Duck* was due to the static nature of its gameplay, which did not incorporate the player's body into the experience. This principle highlights the importance of physicality in MR, as demonstrated in games like *The Duel*, where the player's body serves as the primary interface with the game world. This approach not only boosts immersion and engagement in MR experiences but also encourages active participation and movement.

7.2 Limitations and Future works

Our exploration into SCMR opens avenues for future research, while also acknowledging certain limitations of our current study:

7.2.1 Coexistence of Multiple SCMR Experiences. Future work could investigate how multiple SCMR instances might interact or coexist within the same physical space. Understanding potential synergies or interferences among concurrent SCMR games is vital as the presence of these experiences in public spaces grows.

7.2.2 Physical Contact Interaction. Since it's hard to recognize bodily contact interactions based on current mixed reality systems, we limited MOFA and its game to remote attacks without physical contact within first-person shooter (FPS) mechanics. Future investigations into SCMR games that include physical player interactions could provide valuable insights for creating richer, more tactile, and immersive experiences.

7.2.3 Interaction with the Physical World. MOFA did not use physical dynamic meshing due to the limitations of current mixed reality technology for multiplayer mesh synchronization. Leveraging the physical environment more deeply in SCMR experiences remains an area for exploration. Future designs could integrate digital content that interacts with physical surroundings, enriching the gameplay and making the game space more engaging and contextually responsive.

7.2.4 Expansion of the Design Space. The five prototype games we developed offer only an initial insight into the vast potential of SCMR. This design space is yet to be fully explored. By making the MOFA framework open-source, we aim to inspire more developers to venture into this relatively untapped field.

8 CONCLUSION

As consumer Mixed Reality (MR) devices become more widespread, it's increasingly important to create SCMR experiences that are engaging, inclusive, and seamlessly integrated into public spaces. In this work, we explored the design space of SCMR through engaging game design and user studies. We hope our open-source MOFA framework will pave the way for further exploration in game design for SCMR, inviting a broader community of developers and researchers to contribute to this emerging field.

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A IMPLEMENTATION OF COORDINATION REGISTRATION IN MOFA

A.1 Objective

Let $\mathcal{P} = \{\mathbf{p}_1, \mathbf{p}_2, \ldots, \mathbf{p}_n\}$ which is the QRCode image position in Host's coordinate system and $\mathcal{Q} = \{\mathbf{q}_1, \mathbf{q}_2, \ldots, \mathbf{q}_n\}$ which is QRCode image position in client's coordinate system sampled by client's image tracker. $\mathcal{P}$ and $\mathcal{Q}$ are two sets of corresponding image positions by sampling at different timestamps.

Because ARKit coordinate system's y-axis is parallel to gravity, and its origin is the initial position of the device, we wish to find a rigid transformation that optimally aligns the two sets in the least squares sense, i.e., we seek a rotation

$$\mathcal{R}_y(\phi) := \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix}$$

and a translation vector $\mathbf{t}$ such that

$$(\phi, \mathbf{t}) = \underset{\phi\in\mathbb{R}, \mathbf{t}\in\mathbb{R}^3}{\arg\min} \sum_{i=1}^{n} w_i \|(\mathcal{R}_y(\phi)\mathbf{p}_i + \mathbf{t}) - \mathbf{q}_i\|^2$$

where $w_i > 0$ are weights for each point pair.

A.2 Computing the translation and the rotation

Assume R is fixed and denote

$$F(\mathbf{t}) = \sum_{i=1}^{n} w_i \|(\mathcal{R}_y(\phi)\mathbf{p}_i + \mathbf{t}) - \mathbf{q}_i|^2$$

We can find the optimal translation by taking the derivative of w.r.t $\mathbf{t}$. It implies

$$\mathbf{t} = \bar{\mathbf{q}} - \mathcal{R}_y(\phi)\bar{\mathbf{p}}$$

where

$$\bar{\mathbf{p}} := \frac{\sum_{i=1}^{n} w_i \mathbf{p}_i}{\sum_{i=1}^{n} w_i}, \bar{\mathbf{q}} := \frac{\sum_{i=1}^{n} w_i \mathbf{q}_i}{\sum_{i=1}^{n} w_i}$$

In other words, the optimal translation $\mathbf{t}$ maps the transformed weighted centroid of $\mathcal{P}$ to the weighted centroid of $\mathcal{Q}$.

We can find the optimal rotation by taking the derivative of w.r.t ϕ

$$\phi = \arctan \frac{\left(\sum_{i=1}^{n} w\_i(\mathbf{p}'_{i,x}\mathbf{q}'_{i,z} - \mathbf{p}'_{i,z}\mathbf{q}'_{i,x})\right)}{\left(\sum_{i=1}^{n} w_i(\mathbf{p}'_{i,x}\mathbf{q}'_{i,x} + \mathbf{p}'_{i,z}\mathbf{q}'_{i,z})\right)}$$

where $\mathbf{p}'_i := \mathbf{p}_i - \bar{\mathbf{p}}, \mathbf{q}'_i := \mathbf{q}_i - \bar{\mathbf{q}}$.

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