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Do, N., Le, K., Fjeld, M. et al (2024). XRPublicSpectator: Towards Public Mixed Reality Viewing in Collocated Asymmetric Groups. Conference on Human Factors in Computing Systems - Proceedings. http://dx.doi.org/10.1145/3613905.3650796

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XRPublicSpectator: Towards Public Mixed Reality Viewing in Collocated Asymmetric Groups

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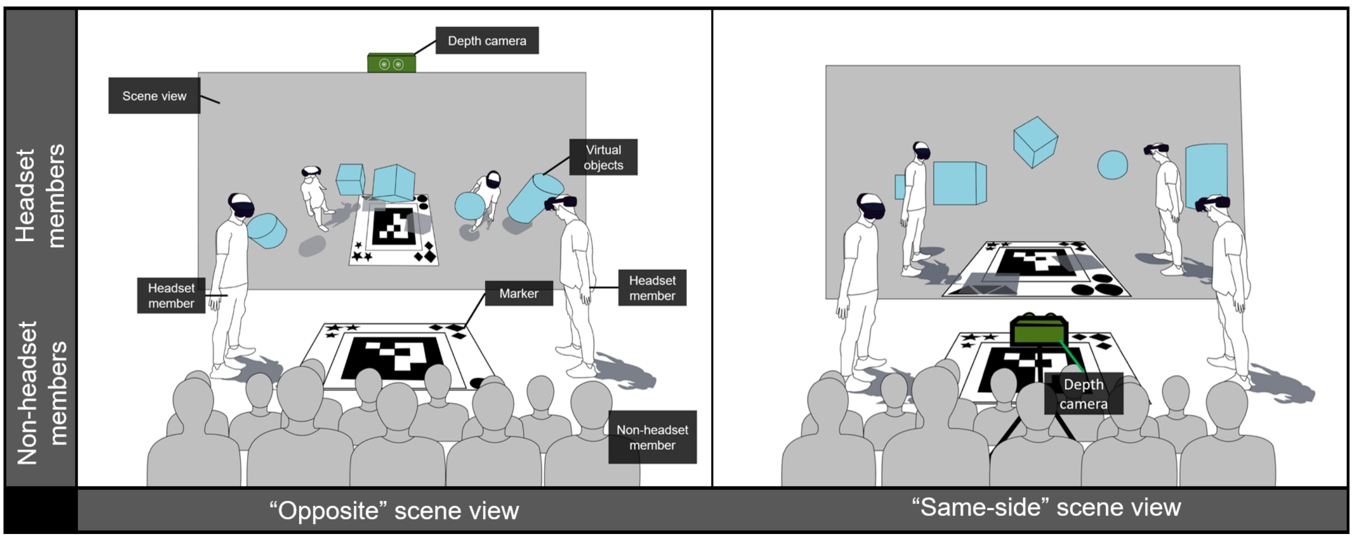

Figure 1: XRPublicSpectator concept and its system elements for on-stage presentation in an collocated asymmetric group: "opposite" scene view from a depth camera mounted on top of the large public display facing non-HMD users (audiences)(left); "same-side" scene view from an on-stage mounted depth camera on the same side with non-HMD users, facing the public display (right). non-HMD users in the same room can still comprehensively perceive the presence and spatiality of virtual objects in the MR space, including those outside the first-person views of users wearing MR HMDs.

ABSTRACT

Mixed Reality (MR) is often viewed and experienced by users wearing specialized head-mounted displays (HMDs) to perceive virtual objects spatially positioned in the users' physical environment. In a classroom or during on-stage presentation, it is often presenters only who are equipped with MR HMDs. However, since spectators most often outnumber presenters, equipping collocated spectators with HMDs to create a shared immersive experience can be costly. This imbalance can result in inefficient presenter-spectator communication and can reduce spectator engagement. To address the need of viewing MR content in such collocated asymmetric groups, we present a concept called XRPublicSpectator. This system utilizes a large display to present a third-person-view of the MR environment constructed by combining RGB-D data of the physical space obtained from a depth-sensing camera with objects from the same virtual environment as tracked by the MR HMDs. Leveraging the XRPublicSpectator concept, we developed an exemplary application which captivated an MR game arena where non-HMD users can watch players performing a duel card game. Results from a preliminary study with the exemplary application show that compared to the first-person MR view, XRPublicSpectator enabled non-HMD

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CHI EA '24, May 11–16, 2024, Honolulu, HI, USA

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ACM ISBN 979-8-4007-0331-7/24/05
https://doi.org/10.1145/3613905.3650796

users to more comprehensively perceive information within the MR environment and potentially improved their engagement with HMD users and MR contents.

CCS CONCEPTS

• **Human-centered computing** → *Interactive systems and tools.*

KEYWORDS

Mixed Reality, Collocated Team, Asymmetric Groups

ACM Reference Format:
Nam Hoai Do, Khanh-Duy Le, Duy-Nam Ly, Morten Fjeld, and Minh-Triet Tran. 2024. XRPublicSpectator: Towards Public Mixed Reality Viewing in Collocated Asymmetric Groups. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24), May 11–16, 2024, Honolulu, HI, USA*. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3613905.3650796

1 INTRODUCTION

Mixed Reality (MR) enriches human vision by adding virtual objects to the the spatial environment surrounding us at real time. Visually perceiving spatial relations among physical and virtual objects can help reduce cognitive load while improving task performance [1, 8] and human communication [17, 21]. MR can also make communication in certain settings more intuitive and engaging at a reasonable cost. For example, when discussing a dinosaur with large dimensions, users can view the virtual dinosaur in MR and intuitively pick up its actual dimension without the need for a full-scale, bulky replica.

Users typically experience MR environments through hands-free devices like wearable MR HMDs. An alternative approach involves handheld devices for MR, but this requires users to physically handle and position the device for content selection, limiting dexterity and causing fatigue [16, 24]. This approach may not be suitable for prolonged tasks, such as attending lectures. Equipping a group of presenters as well as a group of spectators collocated in the same room with MR HMDs or requiring them to hold mobile MR devices, can prove to be economically and socially impractical. A proposed solution is to have presenters exclusively wear MR HMDs, reducing the overall HMD need for collocated spectators, but creating an asymmetry in device usage. To aid non-HMD viewers in perceiving MR content, a common method is to display the HMD users' video feed on a public display. However, relying on a first-person-view (FPV) video may lead to viewer dependence on the presenter and information loss, particularly if virtual objects are outside the HMD user's viewing range. This dependency and information loss may result in decreased engagement and hinder communication and collaboration between HMD and non-HMD users.

To address this, we introduce XRPublicSpectator, which utilizes a large display placed in the space of a collocated asymmetric group engaging with MR content. This display showcases the MR environment in a third-person view (TPV) or scene view, enabling non-HMD users to comprehensively perceive the spatial relationships between physical and virtual elements. The TPV representation of the MR environment is constructed by fusing RGB-D data of the physical environment with objects from the virtual environment provided through the MR HMDs. XRPublicSpectator is based on a simple setup employing a commodity depth-sensing camera combined with the localization capability of off-the-shelf MR HMDs for visualizing the MR environment, aiming for easy deployment. Based on the concept and setup of XRPublicSpectator, we developed an exemplary application captivating an MR arena where non-HMD users can watch two players performing a duel card game in an immersive way. A preliminary study using this exemplary application revealed that compared to video-streamed FPV, XRPublicSpectator allowed non-HMD users to more comprehensively perceive details in the MR environment. Furthermore, the preliminary study also yielded indications that our approach has a potential to enhance spectator engagement with MR content, thereby addressing inefficient presenter-audience communication, consequentially promoting a more inclusive and immersive experience.

2 RELATED WORK

2.1 MR Collaboration in Remote Settings

Collaboration in MR has often been studied in remote settings where a person acts as an instructor guiding a remote worker wearing an MR HMD to complete a physical task. Commonly, the instructor observes the worker's workspace either from the worker's FPV or from the scene view on a desktop while giving instructions [2, 9, 22]. Alternatively, recent works [3, 15, 18–20, 25] explored remote dyad collaboration setups between MR and VR collaborators, where the VR user can immerse in the virtual copy of the MR collaborator's space. In general, these works have shown that in remote settings providing the scene view of the MR worker's workspace allows the instructor to avoid dependency on the MR user's FPV, which was termed as "view independence". In addition to that, the scene view also provides the remote instructor with a better overview on the workspace, resulting in more efficient collaboration. However, it remains unclear if providing a scene view of the MR space would benefit non-HMD users in collocated groups, where they can see bodily movements and behaviors of collocated HMD users. XRPublicSpectator is our endeavor towards answering this, and related question. Aside from collaborative instructional tasks, the need for remotely spectating real users in a virtual scene has also been emerged in the context of game livestreaming. Hartman and Vogel [6] provided remote spectators with the 3D reconstruction of the current game scene to allow them to individually control their personal game view, increasing their immersion in the remote game watching. Similarly, DreamStream [27] captures and reconstructs the 3D representation of a VR game player and put it into the VR game environment he/she is playing, which will be live-streamed and watched by remote spectators. Also in the context on remote spectating, WebTransceiVR [13] is a web-based VR streaming platform that allows remote spectators to choose viewing the VR environment being streamed from different actors' perspectives. Overall, these systems target remote collaboration settings which require spectators to use personal computers to view the content. Considerably closest to our work, XRStudio [14] offers a MR live-streaming interface where remote students through their personal computer can view virtual environment fused with the teacher's image from TPV to experience immersive online lectures. While many students showed their favor for this online lecture interface, it still remains unclear if similar interfaces could benefit non-HMD users in viewing MR contents being operated by collocated HMD users.

2.2 MR collocated collaboration

In asymmetric collocated group contexts, Thoravi et al. [26] developed and studied TransceiVR - a collaborative system that allows a user using a tablet to collaborate in a virtual environment with a collocated collaborator wearing a VR HMD. Kudo et al. [11] explored a design to represent bystanders' presence and location in the virtual environment being viewed by a VR user to improve his/her awareness of changes in the space. Yet, this system was unable to support bystanders without MR HMDs to perceive what the VR user was seeing. Yu et al. [30] proposed a collocated collaboration setup where each collaborator wore an MR HMD to view the live captured 3D point cloud of the workspace of the other while being able to generate annotations for instruction. However, this setup requires all users to be equipped with an MR HMD, not practical for larger groups, such as in a classroom or an auditorium presentation. Facedisplay [5] instrumented a VR HMD with world-facing touch displays showing the virtual environment of the VR user to allow bystanders to perceive and interact with what a VR user is seeing. While this approach is suitable for personal uses, it is not a good fit for collaborative groups due to limited screen sizes of world-facing displays. HMD Light [29] projects the current first-person view of a VR user on a surface in the surrounding physical environment (like a floor) and supports the user to perform collaborative activities with external users on the projection. Using a similar approach, Jansen et al. [7] projects the first-person view of an AR user on a physical surface to allow HMD and non-HMD users to collaborate on the same workspace. ShareVR [4] facilitates non-HMD users in observing the VR user's perspective by projecting the 3D virtual environment onto the shared physical space floor. However, this horizontal projection can result in spatial information loss and challenges in viewing for collocated non-HMD users, particularly in large spaces such as auditoriums. Compared to these above systems, XRPublicSpectator aims to provide an interface that can provide non-HMD users with a view-independent ability to effectively perceive MR contents in such relatively large collocated group contexts.

3 XRPUBLICSPECTATOR - PUBLIC VIEWING OF MR ENVIRONMENT

The XRPublicSpectator concept is designed to facilitate the observation of the MR environment by non-HMD users within a co-located group. This observation is made possible through a public large display positioned within the physical space of the group. This concept capitalizes on a familiar arrangement commonly found in various real-life scenarios, such as a teacher delivering lectures in a classroom or a speaker presenting to an audience in an auditorium. In these situations, presenters routinely utilize public large displays to showcase their presentation slides. This well-known practice enables the seamless integration of the XRPublicSpectator setup into such environments. On the public large display, non-HMD users can view the MR environments from a scene view or third-person perspective, which should provide them with comprehensive understandings of the spatial relationships between physical and virtual entities or individuals. To capture and present the scene view of the MR space, XRPublicSpectator employs a readily available depth-sensing camera capable of obtaining RGB-D data. Depending on the deployment context, the camera can be strategically positioned to encompass the entire area where HMD users engage with MR content.

The RGB-D data, encompassing images of HMD users within the space, is initially visualized in a virtual 3D environment. Subsequently, the virtual objects manipulated by HMD users must be seamlessly integrated into this virtual space while maintaining their spatial relationships with physical entities in the scene. This integration corrects the spatial arrangement perceived by HMD users. For instance, if a virtual object is situated behind a physical object and obstructed from the perspective of the scene camera, this relationship and obstruction must be accurately reproduced on the public display. XRPublicSpectator's scene view dynamically reflects such spatial relationships in real-time, ensuring timely updates as changes occur to physical objects and virtual content within the MR environment.

When HMD users introduce a new virtual object or modify the position, scale, or rotation of an existing one, potentially leading to spatial alterations in the MR space, these changes are promptly depicted on the scene view. XRPublicSpectator accomplishes this by monitoring the positions of HMD users and the relative positions of virtual objects in the MR space. Notably, XRPublicSpectator employs a simple setup without requiring high-end motion capture systems as in previous works [4, 22]. Yet, it is still able to continuously track HMD users' spatial positions.

In the XRPublicSpectator setup, a marker placed in the MR environment, such as on the stage floor, is detected by the scene-view camera using RGB (Fig. 1). The marker's 3D position relative to the camera, estimated based on the depth information, serves as the origin for constructing the MR environment's coordinate system from the captured 3D point cloud. When a HMD user enters the room, the MR interface prompts them to focus on the marker. Upon detection by the HMD (Microsoft Hololens 2 in our prototype), the initial relative position between the HMD and marker is established using RGB-D information. Subsequently, each HMD's relative position is continuously updated based on its built-in sensors and cameras. This information determines each HMD user's position in the MR environment relative to the scene camera's coordinate system.

When a HMD user introduces a virtual object, its relative position to the HMD, combined with the HMD's current MR space position, calculates the object's position relative to the scene camera. This approach enables XRPublicSpectator to reconstruct the scene-view representation of the MR space using a simple hardware setup deployable in diverse environments. The resulting scene view provides non-HMD users with a comprehensive perspective of the entire MR space, aiding in the perception of physical and virtual objects and facilitating an understanding of their relative spatial relationships, even if some objects are beyond the HMD users' field of view.

Prototype implementation:
In our latest prototype, we use a Zed camera [12] to obtain RGB-D data of the physical space and Vuforia SDK [28] to detect the marker. both the public display and MR HMD applications were implemented using Unity. The application for Microsoft Hololens 2 MR HMDs is developed using the Mixed Reality Toolkit.

In this prototype, we explored two scene-view camera positions: one on the side of the large public display and the other on the same side as non-HMD users (as shown in Fig.1). These setups offer distinct perspectives of the MR space. The former yields a mirrored representation ("opposite" scene view), revealing obscured sides to the audience, while the latter captures the sides facing non-HMD users ("same-side" scene view).

These representations have their merits and drawbacks. The "opposite" scene view enables non-HMD users to observe obscured sides but may pose cognitive challenges due to incomplete representations of the sides visible to them in reality (Fig. 1(a)). Conversely, the "same-side" scene view enhances non-HMD users' view in reality with virtual objects but may be less effective in perceiving objects on the obscured sides (Fig. 1(b)).

4 PILOT STUDY WITH AN EXEMPLARY APPLICATION

4.1 Exemplary Application

We developed an exemplary application based on the proposed apparatus of XRPublicSpectator and conducted a preliminary user study on this application to garner initial insights on its utility and usability. Drawing inspirations from the well-known fictional comic series Yu-gi-oh [23] and its associated video game [10], we developed a mixed-reality card-based battling game, named XRDuelMonsters. In this game, two players engage in a trading card battle featuring characters (e.g., monsters) and magical artifacts. Once playing a card, the holographic representation of the character or artifact becomes visible to both players and any nearby spectators. Following the original game concept in the comic, both the players and the spectators could witness the holographic characters or objects co-exist in the same spatial environment and positioned proximately to their respective owners. This should not only foster a hightened sense of immersion, for both the players and the spectators, but also enable spectators to discern the possession relationship between players and characters based on their spatial arrangement.

Leveraging the setup of XRPublicSpectator, each player in the dual wears an MR HMD, complemented by a public large display for onsite spectators to observe the dual gaming environment (Fig.2(a)). Utilizing their MR HMDs, players can strategically position virtual cards in their surroundings (Fig.2(a)). Once a card is activated, the 3D representation of the corresponding character emerges from the card, positioned in close proximity to the player who owns it. The scene view of the MR game space will be shown on the public large display where collocated spectators can see not only the movements and behaviors of the players but also all game characters which have been played. The incorporation of MR HMDs facilitates an immersive gaming experience for players engendering a sensation of coexistence with the virtual game characters and artifacts in a shared environment. Additionally, the scene view of the MR game space offers the audiences a global perspective of an environment where the real players and virtual game characters seamlessly blend into the same spatial context in real-time. This real-time integration serves to enhance the audience's excitement and engagement with the game.

4.2 Preliminary User Study

We conducted a preliminary study with XRDuelMonsters to gather initial insights on the utility and usability of XRPublicSpectator. We were interested in validating if XRPublicSpectation could improve spectators' ability and experience in viewing MR contents operated by collocated HMD collaborators. Our primary research question in this preliminary study is whether displaying TPV visualization of the MR environment enabled by the XRPublicSpectator setup could help collocated non-HMD members in an asymmetric group perceive the spatial relationship between virtual and real objects more effectively, as compared to the common approach of showing the HMD member's FPV.

4.2.1 Study setup. We invited 8 students (3 males and 4 females), aged 19 to 21 at our university to participate in the study. However, one could not show up due to personal reasons, resulting in 7 participants in total. The participants had basic to moderate computer literacy and had never experienced MR before. Employing a within-subject design, our study aimed to investigate whether XRPublicSpectator had the potential to enhance the perception and experience of collocated spectators compared to a baseline condition. In the baseline condition, spectators typically observed MR environments by looking through the FPV of the users wearing HMDs (Fig. 2(b)), as opposed to the TPV offered by XRPublicSpectator.

We organized the 7 participants into two groups - one group with 4 participants and the other with 3 participants. Each group underwent two trials, during which its users respectively observed two game matches enacted by two players, performed by two users of the research team. In the baseline condition, the two players' FPV live video feeds were shown side-by-side on the public display (Fig. 2(b)). For the XRPublicSpectator condition, in this preliminary study, we used the same-side scene view setting. We used a 75-inch screen as the public display in this study. Counter balancing was applied to alleviate the influence of order effects and bias. Specifically, the first group observed the two players engaging in a match through the baseline condition, followed by XRPublicSpectator. Conversely, the second group performed the same observation but with the XRPublicSpectator first. In each trial, participants were equipped with a deck of five cards, each featuring a distinct character, with no overlap between the cards held by the two players. Sequentially, players took turns playing their cards, triggering the positioning of the associated character's 3D model 1.5 meters behind its owner. Players had the option to designate a character for defense or attack against their opponent. When a character was defeated, its corresponding card was also removed. For simplicity, a match concluded when one of the two players did not have any card remained.

After each trial, participants responded to a questionnaire comprising four questions. The initial three questions delved into the

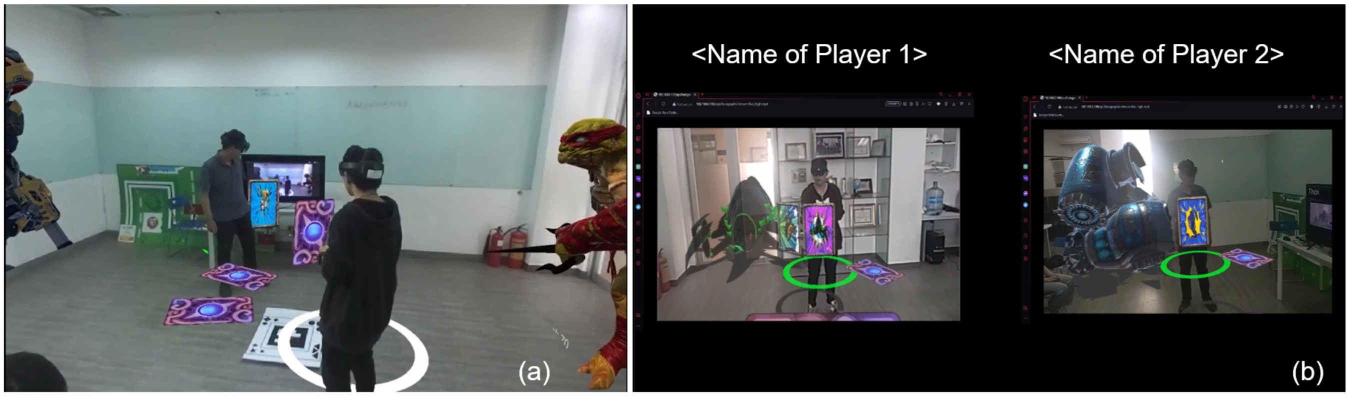

Figure 2: (a) XRDuelMonsters: close-up of the public display showing the "same-side" scene view. Each player is surrounded by his own cards and their monsters are located nearby them. Some cards and virtual monsters are obscured by the players in the scene, illustrating spatially aware representation of the view. (b) Baseline interface condition in the preliminary study showing the FPVs of the two players. In the study, <Name of Player 1> and <Name of Player 2> were replaced by the actual names of the two players.

impact of the two interface conditions on participants' ability to observe and follow the match. These first three questions include:

- **Q1** Which player does this monster belong to? (With the image of the monster attached)
- **Q2** Who was the winner?
- **Q3** Where was the monster standing relative to its owning player?

With Q1 and Q2, participants provided their answers by selecting one out of five options as follows: *Surely <Name of Player 1>*, *Maybe <Name of Player 1>*, *I don't know*, *Maybe <Name of Player 2>*, *Surely <Name of Player 2>*. Note that the participants had been familiarized with the players' names at the beginning of the study session. With these questions, we classified the participants' answers as: *Confidently incorrect*, *Unconfidently incorrect*, *No answer*, *Unconfidently correct* and *Confidently correct*. With Q3, the participants selected one of the following five choices to answer: *On the left side*, *On the right side*, *In front of*, *Behind*, *I don't know*. Consequentially, participants' answers for this question were classified either as correct or incorrect.

The fourth question (**Q4**) asked the participants to rate their agreement for the statement "I can easily observe all aspects of the game (game characters on both sides, turns, match outcomes, etc.)" on a 7-point scale (1 means Strongly Disagree and 7 means Strongly Agree). Besides that, we also collected participants' qualitative feedback in a post-study interview.

4.2.2 Initial insights. Overall, participants' responses for the questionnaires demonstrated noticeable benefits of XRPublicSpectator compared to the baseline interface condition (Fig. 3). For Q1, using XRPublicSpectator, all 7 participants correctly identified the owners of the given monsters (5 confidently, 2 unconfidently) compared to only 3 correct (2 confidently, 1 unconfidently), 1 confidently incorrect and 3 no-answer responses in the baseline interface. Similarly, utilizing XRPublicSpectator, all participants exhibited perfect performance (confidently correct) in identifying the victors of the game matches. Conversely, with the baseline interface, 4 participants accurately identified the winning players with a high degree of confidence. Two participants, also with a high level of confidence, provided incorrect responses, and one participant was unable to ascertain the winner. Moreover, with XRPublicSpectator, all participants demonstrated superior proficiency in discerning the spatial relationship between monsters and their respective owners (5 confident, 2 unconfident). This is contrast to the baseline, where only 4 participants provided correct responses with high confidence, while 3 participants proffered incorrect responses with high confidence. Furthermore, ratings for Q4 revealed that participants perceived XRPublicSpectator much more easier for them to observe different details of the game (5.14 vs 2.86).

The post-study interview's data yielded interesting insights explaining the differences in participants' performance in spectating the MR game matches as shown in the quantitative results above. Five out of seven participants stated that FPV of the baseline condition made them feel somewhat dependent on the person wearing the MR HMD (*"Sometimes, the constant shifting of the viewpoint by the player makes it hard for me to keep up and grasp the information"*, ***P3***). Players' frequent head movements in the MR game led to a disrupted viewing experience on the FPV interface, posing challenges for the participants to follow a specific monster or event in the game. To comprehend a monster's position relative to a player, participants had to simultaneously monitor players' physical movements, especially their looking direction, and observe the corresponding FPV video feed on a large display. The instability of the FPV video feed due to head movements made it mentally demanding for participants to construct the complete MR environment in their imagination. Inherently, this led to their confusion and uncertainty about which player was controlling which monster, the number of remaining cards of each player or where a monster was positioned in the game space.

On the other hand, the XRPublicSpectator interface created less cognitive demands for participants in monitoring what the players were doing and what was happening in the game. Particularly, most

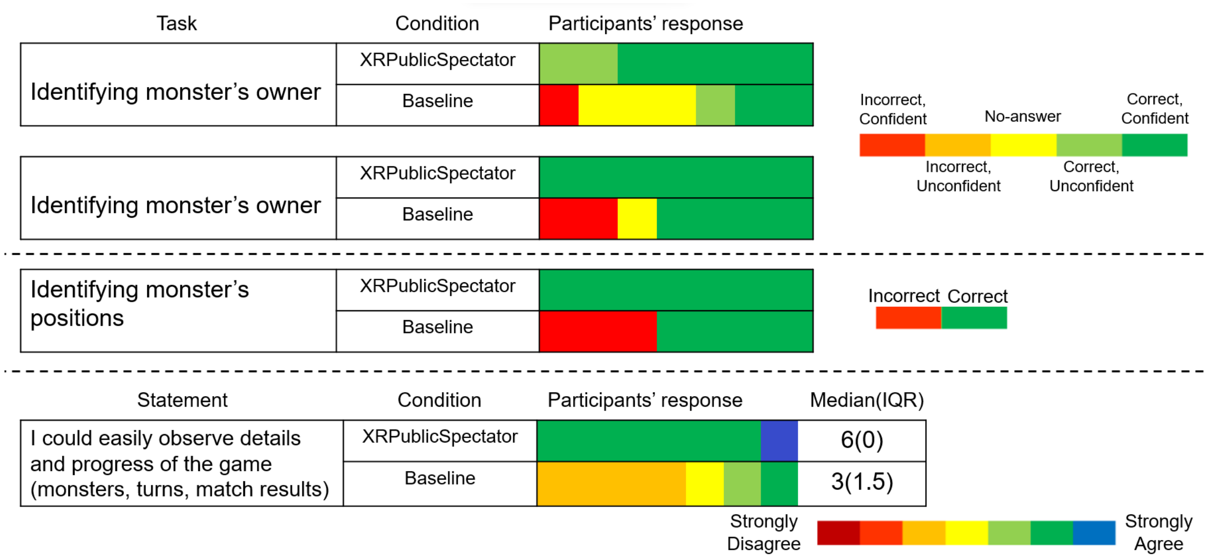

Figure 3: Detailed quantitative results from the preliminary study including participants' understandings of and overall perceived easiness in following the game matches.

participants reported to predominantly focus on the MR content on the public display as this comprehensive view encompassed the entire game space, offering adequate information of the positional arrangement of monsters and their responses to players' behaviors. Nonetheless, some participants primarily focused on the players and their gestures in real life, occasionally checking the large display for virtual card and monster updates. Despite switching between physical space and the MR content on the display, they did not feel any confusion or mental strain, as the MR content's perspective on the large display was consistent with their view of the physical game space.

Moreover, using XRPublicSpectator, participants seemed to be more engaged in the performance of the players, probably thanks to their adequate understanding on the entire MR environment. P5 reported that when she saw one of the players struggle to locate his monster (partially due to the narrow field of view of the MR HMD), she actually informed him that the monster was behind him. Additionally, one participant suggested to combine XRPublicSpectator with the FPV representation offered by the baseline to leverage the advantages of each interface in order to allow spectators to dynamically observe the game from different perspectives. (*"I would like to combine these two perspectives and add a first-person view to XRSpectator. This way, besides the overall observation of the game, I can also switch to the first-person view occasionally to closely observe the skills and actions of that player, similar to common view perspectives in competitive first-person-shooter games."* (***P3***))

5 FUTURE WORK

In our upcoming research, we plan to delve deeper into understanding how different viewing conditions influence spectators' perceptions of MR environments represented on collocated large shared displays. We will specifically investigate potential variations in spectators' performance and experiences across three conditions: "same-side" scene view, "opposite" scene view, and a blend of FPV and TPV. To gain more insights, we will consider incorporating gaze tracking to obtain information of how spectators allocate their attention between the MR content on the large display, the collocated users and artefacts in the real world. This approach could offer a more nuanced understanding of the impact of viewing conditions on spectator engagement, performance metrics, and attention distribution in MR collaboration of collocated asymmetric groups. Furthermore, future works will also need to investigate approaches to allow non-HMD users to effectively elicit their non-verbal cues (e.g., deictic gestures) in their communication with HMD users on MR contents.

ACKNOWLEDGMENTS

This research is funded by Vietnam National University, Ho Chi Minh City (VNU-HCM) under grant number DS2024-18-01.

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