Facilitating Asymmetric Collaborative Navigation in Room-Scale Virtual Reality for Public Spaces

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Abstract. This study investigates asymmetric collaboration in public room-scale Virtual Reality (VR) setups to address the isolating experience provided by single-user Head-Mounted Displays (HMDs). In our field study, participants wearing an HMD had to find their way in a virtual maze with the help of co-located participants without an HMD. The non-HMD participants could either see a mirrored HMD view, a map of the maze, or a combination of the two. We evaluated which of these three conditions facilitates more collaboration and engagement for the non-HMD participants and spectators, as well as the HMD participants. Our findings can be used when facilitating engaging asymmetric experiences for public VR setups.

Keywords: Virtual reality · Asymmetric collaboration
Room-scale virtual reality · Visualization · Public spaces
Computer graphics

1 Introduction

Virtual Reality (VR) is of growing interest for public cultural centers such as museums and libraries that are increasingly often setting it up for the public to present cultural information. It has become a new way of providing information and entertaining their visitors [1,2]. The technology has brought new advances such as room-scale virtual reality that is capable of allowing people to freely move around in the play area as they walk and explore a virtual environment. One of the limitations of this technology is that single Head-Mounted Displays (HMDs) can be worn only by one person at a time, which often means that the other people standing by the setup cannot engage in the experience [2,3].

The single-person experience is an important limitation specifically for public cultural centers that are devoted to large groups of visitors [2]. There have been attempts to bring a social experience into VR, such as using multiple HMDs to bring several users into the same virtual environment. However, this is currently a costly setup for public centers who have to manage large groups of visitors.

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In commercial products like VR The Diner Duo [4] and Keep Talking and Nobody Explodes [5], a different approach has emerged that allows for an asymmetric collaboration between one HMD participant and the non-HMD participants. However, there is a lack of research that explores this asymmetric phenomenon for the public setting.

To address this problem, we investigated asymmetric collaboration between the HMD participant in room-scale VR and the non-HMD participants following along on a side display near the VR setup in the scenario of a public cultural center. We compared the views on the side display in three different conditions: a mirrored view of what the HMD participant sees, a map of the virtual environment, and a combination of the two. The comparison investigated their influence on collaboration and engagement of the participants and spectators in the public setting.

2 Related Work

The limitation of a single-person experience in VR can be addressed by creating an asymmetric collaboration, which is rarely considered for public VR setups. Several studies [3,6–9] that support collaboration and multiplayer experiences made use of similar building blocks. These include unification of participants' experiences through story and theme, use of multiple media, assigning different roles, and emphasizing communication.

Schmitz et al. [8] explored role-based asymmetric collaboration using a media combination of Oculus Rift and CAVE. They gave participants a collaborative task to maneuver a ship around a sea, which was split into two roles – the captain and the crew. In Liszio and Masuch's [3] game Lunar Escape, participants used an Oculus Rift DK2 and two tablet PCs to fulfil a collaborative task. Similarly, in the game Keep Talking and Nobody Explodes [5], users collaborate to defuse a virtual bomb, where one wears an HMD and the other uses a paper manual.

Sajjadi et al. [6] studied the influence of the medium on the participants' game experience and collaboration in serious collaborative games. In their maze-game, participants were given two media – one Oculus Rift and one set of Stifteo cubes. The participant wearing the Oculus Rift was presented with an overview of the maze and obstacles in VR and was able to direct the other participant with the Stifteo cubes to safely find a way out of the maze. Results from their study showed no significant difference between the two media, implying that both participants found their experience equally positive.

These studies show the importance of roles and media, as these mean that participants have to depend on each other's abilities and communicate in order to accomplish the objectives. However, related work has not evaluated the effect of using a side display as means of asymmetrically involving the non-HMD participants for public VR setups. A typical public VR setup could have one HMD and a side display placed close by, showing the virtual environment. In this setup, we compared the different views on the side display to investigate their influence on collaboration and engagement of non-HMD participants, spectators, as well as HMD participants.

3 Materials and Method

3.1 The VR Experience

To explore how the view presented on the side display influences the asymmetric collaboration, a VR experience with two roles was set up for a public library. The non-HMD participants were assigned a navigator role and used a map of a maze on the side display to assist the HMD user, who took the role of an explorer and had to find the way to a diamond in the maze.

The VR setup consisted of the HTC Vive HMD and its Lighthouse bases to provide room-scale tracking in a 2.5 m × 2.5 m area, and a regular monitor close by. In this setup, the HMD role had an ability to freely walk in a large virtual maze, which was designed to fit in the 2.5 m × 2.5 m physical space using self-overlapping architectures [10]. In two conditions, the non-HMD role had information about the overview of the maze and location of the diamond on a map, and had therefore an ability to direct the HMD participant towards the goal. Figure 1 shows the design of the VR experience with the maze and the map.

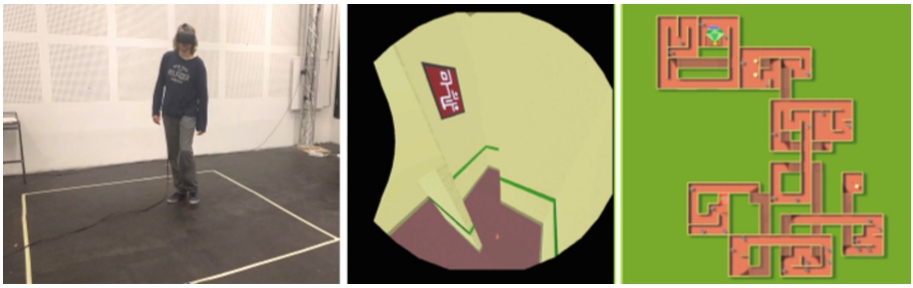

Fig. 1. The 2.5 m × 2.5 m physical space (left), the self-overlapping maze as seen in the HMD (middle), and the map of the maze with the diamond (right)

3.2 Experiment Design

The experiment was set up as an observational study, where three conditions were tested with different views for the non-HMD participants: the mirror display condition (MIR), where only the HMD user's view was mirrored on the side display, the map condition (MAP), where only the map was shown on the side display, and a third combination condition (COMB), where the side display was split to show both the mirror display and the map. The three conditions for the side display can be seen in Fig. 2.

To compare the three conditions, hypotheses were made to find out which of the conditions facilitates more collaboration and engagement for participants and spectators in a public setup. As discussed in related work, roles are an important element of facilitating asymmetric collaboration; thus one hypothesis was

Fig. 2. The side display in MIR (top left), MAP (top right), and COMB (bottom) conditions

that conditions with the map would encourage more collaboration because participants have different roles with different information and abilities. This would not be the case in the MIR condition because the non-HMD participant does not have unique abilities and information compared to the HMD role. Furthermore when the two map conditions are compared, we hypothesized that the collaboration in the COMB condition would be more effective than in the MAP because in the COMB condition, the virtual world is more unified for both participants. It would therefore be easier for the non-HMD participants to give directions to the HMD participant. Based on these assumptions, the following two hypotheses were formulated about collaboration.

H1: The map in conditions MAP and COMB facilitates more collaboration than only the mirror display in condition MIR.

H2: The combination of the map and mirror display in the COMB condition facilitates a more effective collaboration than only the map in MAP condition.

Besides collaboration, observations were also made for participant engagement in the three conditions. Due to the fact that roles brought about by the map conditions allow both participants to contribute towards a common goal, one hypothesis was that the MAP and COMB conditions would be more engaging than the MIR condition. Furthermore, the mirror display in the COMB condition would make it more engaging than the MAP condition. The following two hypotheses were formulated for engagement of both participants and spectators.

H3: The map in MAP and COMB conditions facilitates more engagement than only the mirror display in MIR.

H4: The combination of the map and the mirror display in COMB facilitates more engagement than only the map in MAP condition.

3.3 Participants

At a public library, the experiment was run for three days, with the conditions MIR, MAP, and COMB assigned on different days. 20 participants tried the MIR condition, where one was female and 19 were male with their ages estimated between 10 and 28 years ($M = 16.35$, $SD = 4.6$). The MAP condition was tried by 23 participants, three female and 20 male, whose estimated ages were between 4 and 40 years ($M = 16.09$, $SD = 11.07$). Lastly, 28 participants tried the COMB condition, of which 13 were female and 15 male, and their estimated ages were between 7 and 34 years ($M = 15.07$, $SD = 7.44$). Figure 3 shows images of participants during the experiment.

Fig. 3. HMD participant walking in the VR maze (left) and non-HMD participants using the side display (right)

3.4 Procedure

Participants were instructed at the start that their task is to collaborate to find a diamond in the maze, and the HMD participant was helped to put on the HMD. Their playthrough was observed by two observers nearby. One playthrough was considered to be the period from when participants started to move in the maze until they either found the diamond or stopped the experience due to giving up, changing roles, or the system breaking. As is summarized in Table 1, for each playthrough, the observers noted which roles participants had and how they used them, communication, engagement, spectators, and participants' comments. Communication was counted as utterances for the HMD and non-HMD participants, where one utterance was considered as a piece of speech when a person starts talking until holding a clear pause or until another person starts talking. Two-way communication was also observed, where each utterance of the HMD participant that is replied to by the non-HMD participants or vice versa was counted as one instance.

Observations for engagement included how many times participants tried the HMD and non-HMD role. Spectators were also counted based on their involvement in the experience as passive, moderate, or active. Passive spectators would be considered as people standing nearby and watching, while moderate were people who approached to watch the side display. Lastly, the active spectators would be the ones who approached the side display and helped to guide the HMD participant at some point during the playthrough.

Table 1. Observations noted in the experiment

Topic	Observations
Collaboration	How they use their roles
	Amount of communication: HMD and non-HMD utterances, two-way communication
Engagement	Playthroughs per participant
	How many try one role more than once
	Do they complete the maze
	Number and involvement of spectators: passive, moderate, and active

4 Results and Discussion

The observations from the experiment were analyzed using statistical tests with a significance value of $\alpha = 0.05$. During the experiment, participants in the MIR condition made a total of 18 playthroughs, in the MAP condition 29 playthroughs, and in the COMB, 40 playthroughs were made.

4.1 Collaboration

The system's ability to facilitate collaboration in the different conditions was evaluated by observing whether the participants used their roles, thus contributed to the goal, how much they communicated, and what directions they used. Pearson's chi-squared test showed that there was a significant difference for use of roles (MIR 83%, MAP 97%, COMB 100% used roles), however this was not significant in post-hoc pair-wise comparison tests.

For communication shown in Fig. 4, Tukey HSD test showed that the MIR condition ($M = 4.04$), $p = 0.049$, and COMB condition ($M = 3.84$), $p = 0.03$, had significantly more HMD participant utterances per minute compared to the MAP condition ($M = 2.50$). Similarly, MIR ($M = 13.50$) had significantly more two-way communication than MAP ($M = 6.48$), $p = 0.0002$, and COMB ($M = 9.48$), $p = 0.046$. Further, the COMB condition encouraged significantly more two-way communication, $p = 0.006$ than the MAP condition. Although the MIR condition had most two-way communication, observations indicated that this communication consisted mainly of participants discussing at junctions about where to go next and whether they have been at the same place before: "don't go back here, I think it's a dead end" or "wasn't that the way you came from?".

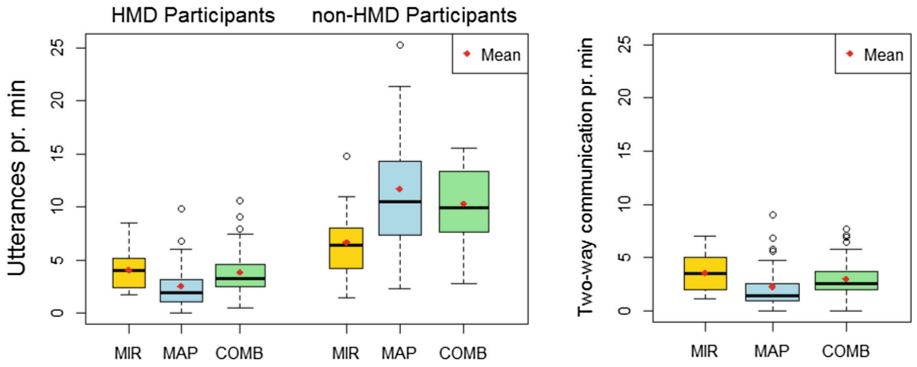

Fig. 4. HMD and non-HMD participant utterances per minute (left) and two-way communication per minute (right)

In contrast to the HMD participant making more utterances in the MIR condition, the non-HMD participants had significantly more utterances per minute in the MAP condition ($M = 11.69$), $p = 0.0003$, and the COMB condition ($M = 10.28$), $p = 0.01$, than in the MIR condition ($M = 6.64$). From observations, this difference in non-HMD utterances in the MAP and COMB conditions was due to the non-HMD participants giving directions, and guiding the HMD participants towards the goal. The communication in the COMB condition was however similar to the MIR condition with regards to HMD utterances and two-way communication, but with many more non-HMD utterances. With the use of roles not having significant differences, the data from communication alone has not shown enough evidence for accepting the hypothesis *H1* that the map conditions MAP and COMB would facilitate more collaboration than the MIR condition. It could therefore be reasoned that merely observing utterances might not be sufficient for accurately evaluating collaboration. Also the fact that the participants in all conditions were instructed to collaborate on completing the goal may have made them feel as if they were required to talk. On the other hand, the communication results showed that the two map conditions encouraged the non-HMD participants more to collaborate than the MIR condition. The hypothesis *H2* that compares the MAP and COMB conditions can be accepted as the COMB condition, where the participants' world was more unified, facilitated more effective collaboration than the MAP condition.

4.2 Engagement

The three conditions' ability to facilitate engagement in the participants has also been analyzed. This was measured through number of playthroughs, spectators and completion rate to evaluate hypotheses *H3* and *H4*. Observations showed that participants had an engaging experience with both roles in all conditions and nine people said that it was "cool", one said that "it was not bad to walk around" and that he "never tried to control virtual reality before – it was fun".

For the playthroughs shown in Fig. 5, Dunn's multiple comparison test showed that there were significantly more playthroughs per participant in COMB ($M = 3.11$) than in MIR ($M = 1.90$), $p = 0.02$, and MAP ($M = 2.78$), $p = 0.03$. A participant would also try the non-HMD role significantly more times in COMB ($M = 1.89$) than in MIR ($M = 1$), $p = 0.008$. There was no significant difference when the COMB condition was compared to the MAP condition ($M = 1.74$), $p = 0.08$. Furthermore, trying the HMD role was not significantly different across conditions, $H(2) = 3.12$, $p = 0.21$. Significantly more participants retried one role several times in MAP (52%), $p = 0.03$, and COMB (89%), $p < 0.0001$, compared to MIR (17%) and in COMB compared to MAP, $p = 0.007$.

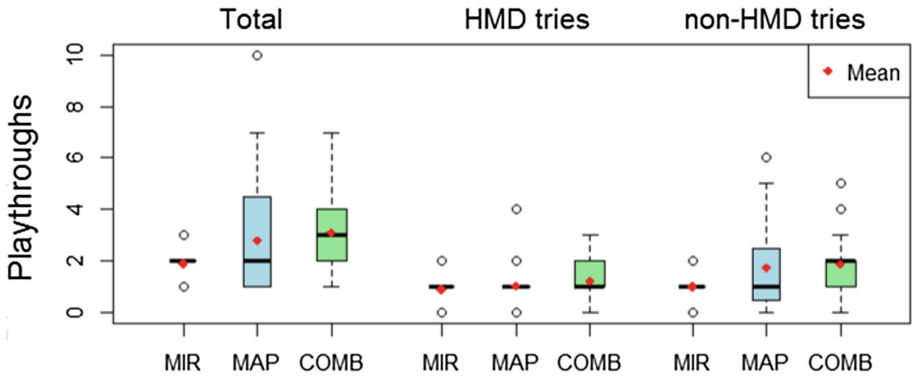

Fig. 5. Number of playthroughs, and tries of the HMD and non-HMD role per participant

The MAP condition ($M = 6.31$) had the most amount of total spectators, as shown in Fig. 6, compared to MIR ($M = 2.17$), $p < 0.0001$, and COMB ($M = 2.88$), $p < 0.0001$. Out of all spectators, the percentage of those who actively directed the HMD participant was significantly higher in MAP (21%), $p = 0.007$, and in COMB (26%), $p = 0.003$, than in MIR (3%). This suggests that MAP provided the most engaging viewing experience. Regarding completion rate, we observed that in more than half (56%) of the MIR playthroughs, participants stopped playing due to frustration, while nobody did in both the MAP and COMB conditions. This also suggests that the MIR condition was overall less engaging. In five out of the 18 playthroughs in the MIR condition, non-HMD participants were observed disengaged and were for instance checking messages on the phone. Six were also observed saying that "I think we are stuck", "we have been all the ways" and one saying "I'd like a minimap". This shows that participants were stuck and disengaged without the map.

Overall, the hypothesis *H3* that the map in conditions MAP and COMB facilitates more engagement than MIR for participants and spectators, can be accepted due to the low completion rate of the MIR condition, the number of retries of one role in the two map conditions, and the high spectator engagement

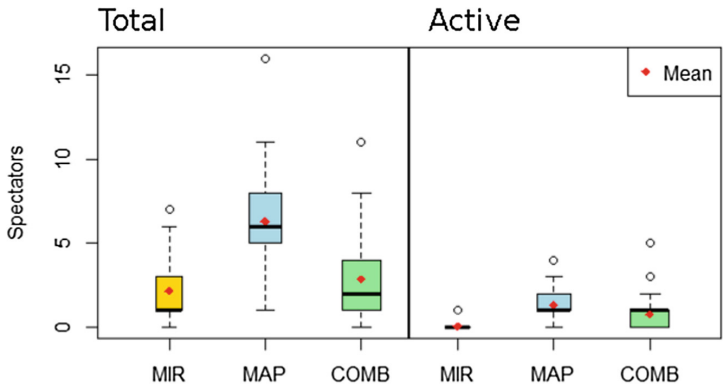

Fig. 6. Number of all spectators (left) and active spectators (right)

of the MAP condition. For hypothesis *H4*, the experiment also showed evidence that the COMB condition facilitates more engagement than the MAP condition for the participants.

5 Conclusion

In this paper, we have addressed the common limitation of HMDs providing only a single-person experience for public room-scale VR setups. To overcome this limitation, the study has proposed and investigated asymmetric collaboration based on different views displayed on the side display for the non-HMD participants. Three conditions, the mirror display, the map, and the combination of the mirror display and the map, were compared in order to find out which condition facilitates more collaboration and engagement for both participants as well as spectators. Based on the statistical analysis of communication between participants, it was not possible to conclude that the two conditions with the map facilitate significantly more collaboration than the mirror display condition. However, the two conditions with the map involved non-HMD participants in the collaboration more than the mirror display condition. In terms of engagement, observations showed that there were significantly more retries and successful completions of the maze in the conditions with the map than in the mirror display condition. There was also a significantly higher number of spectators in the map conditions than in the mirror display condition.

This study has demonstrated how a side display can be used to encourage asymmetric collaboration for a public VR setup. Our findings can be generalized and applied in different areas working with VR setups that aim to include bystanders. This could also be explored in further studies, where inspiration could be drawn from games and interaction theories to create content that can engage the non-HMD viewers even more. Other media such as smartphones that are typically used by people in public places could also be explored for how they can be used as controllers, thus giving the non-HMD role new abilities.

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