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COLLABORATIVE DESIGN REVIEW SESSIONS IN VIRTUAL REALITY: MULTI-SCALE AND MULTI-USER

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Abstract. The use of Virtual Reality (VR) for design reviews in projects is becoming more common in construction. However, the use of VR in these processes has been limited to been used more as a complementary reviewing tool alongside information medias such as 2D drawings and 3D models. Furthermore, immersive VR has been argued to have limitations when it comes to orientation and understanding and reasoning about functional links between physical layouts in a facility. This paper presents a case study of a VR system used during design reviews that support end-users to switch between different representations and scale i.e., miniature model/bird-eye view, and a 1:1 scale experience of the facility. The data gathered, consisted of recorded observation of the VR based design review process and study what type of discussion and design errors that was found during two VR-workshops connected to a new elementary school. The result shows, that by supporting switching between miniature model and 1:1 scale VR experience facilitated spatial orientation and understanding and collaboration across disciplines in the project. The study also show how collaborative immersive VR can be used as an efficient communication-tool during the design process in a real-world project.

Keywords. Virtual Reality; VR; Immersive Virtual Environments; Collaboration; Levels of detail; SDG 4; SDG 9; SDG 11; SDG 12.

1. Introduction

A common challenge during the design process of a building is to provide a representational medium that facilitates understanding and communication among all involved stakeholders. For instance, clients and building end-user often have difficulties to fully understand and comprehend traditional design mediums such as 2D-plans, elevations, sketches, and 3D-models, yet their input and feedback can be crucial in order to obtain a high-quality outcome.

This is especially true for educational facilities where teaching methods and student

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performance is linked to and affected by design choices and physical layout of the school (Frelin and Grannäs, 2020; Byers, Imms, and Hartnell-Young, 2018).

However, in this context, immersive Virtual Reality (VR) has been shown to offer an alternative or complementary representational medium (Mastrolembo Ventura et al., 2019; Sateei et al., 2021). In contrast to traditional design mediums, immersive VR allow all stakeholders to experience and comprehend future buildings from a self-centered, egocentric perspective, which better mimics a real-life experience. Especially for laypersons, such as building end-users, this has been shown to provide another level of understanding and perception of space (Abouelkhier, 2021; Johansson & Roupé, 2019; Roupé et al., 2019; Roupé et al., 2020).

Still, factors such as immature technology, client-contractor dynamics, requirements for implementation and structure and an overall lack of experience have prevented VR from being fully established (Delgado et al 2020). As such, it is important to provide real-world examples on how to successfully integrate VR beyond that of pilot testing (Teixeira et al. 2021). In addition, previous studies have identified limitations with VR compared to 2D drawings in that a user is more likely to get disoriented in a large VR-model, and that it might be less suitable for an easy overview and understanding of the big picture (Liu et al., 2020). With educational facilities being characterized by the importance of functional logistics and communication and flows between spaces, supporting better orientation and easy overview of large projects thus becomes an essential aspect to solve for immersive VR. For the specific case of head-mounted displays (HMDs) it is also important to consider how to support collaboration. With HMDs being primarily a tool for the individual, it makes it less suitable for active collaboration during design review sessions.

In this paper we investigate how collaborative immersive VR can be used as an efficient communication-tool during the design process. The setting is a real-world case where architects and client representatives used VR as the only medium during two design review sessions for a new elementary school. During these sessions empirical data was collected by means of video-recorded observations as well as interviews. In order to support a better overview and aid navigation between different locations in the VR-model we also explored the concept of having easy access to a miniature model within the VR environment. In particular, we are interested in the interplay and relationship between allocentric, and egocentric frames of reference offered by combining full-scale and miniature-scale representations within the same medium. Although previous research has investigated – and advocate – a combination of allocentric representations (e.g., 2D-plans or bird's eye view) and egocentric representations (e.g., immersive VR) throughout the design process (Roupé et al. 2019), far less has been explored in terms of offering these two representations at the same time within the same medium.

2. Method

The case study was to study and investigate a VR based design review process and study what type of discussion and design issues that were found during two VR-workshops connected to a new elementary school. The involved participants were involved and responsible for different parts of the design process e.g., a project manager, development managers (for the school), and an architect responsible for fixed

furnishing as well as an interior architect from the municipality of Gothenburg.

The idea of using VR was recognized when 2D and 3D models could not provide a sufficient level of spatial understanding among the project group.

The study was done on two separate occasions via VR-workshops (n=8 in the first session and n=6 on the second session) at Chalmers University of Technology. Given that the workshops were conducted shortly before construction was about to start, the participants wanted apart from the above-mentioned objective, also investigate how VR could facilitate the planning processes of new school premises from an end-user perspective. In this context, they wanted to investigate how it could mitigate the risk of costly reconstruction close after commissioning.

The workshops were conducted during the detail-design phase of the project with the key objective to use VR as a design review tool to discover any design error that would otherwise be difficult to discover and address with 2D drawings that were the main reviewing tool in the project. Before starting the first workshop, participants were briefed on the aim of the research and subsequently introduced to a VR environment (learning how to navigate and interact within the VR-model). Following this, participants were asked to review operational requirements related to the functionality and workflow. The second workshop was oriented around a more detailed design and room layout, in terms of having furnished spaces to review in the provided VR-models.

During these two workshops, at least one person from the research team was available for supervision and providing help in terms of showcasing how to navigate via the provided VR-hardware. The VR system that was used were three Oculus Rift S kits, together with the software BIMXplorer. The software supported direct import of IFC-files from the design process, without any need for further optimization. Additionally, there were functions such as a measuring tool, taking screenshots, markups, and support for multi-user collaboration. During the VR-workshops, the participants used mentioned hardware kits coupled with a big screen display and two laptop displays, see Fig 1.

Figure 1. The set-up during the first workshop (left). Different participants viewing and discussing potential design issue areas during the second workshop (right).

The methods used in this study were observations (video recorded) during the workshops and a follow up open discussion at the end of each VR-workshop where the participants reflected on their experience. The design error found by the participants have been categorised and mapped to the allocentric and ego-centric display-options enabled in BIMxplorer; a virtual miniature model of the building that enabled

participants to crosscut the virtual model to view the building from a bird-eye perspective (i.e., a digital version of a 2D view) and the 1:1 scale option typically associated with VR-models.

The result was analysed within the theoretical framework of egocentric and allocentric design space representation. This was done to discover patterns in terms of the design issues discovered and discussed among the participants during the workshops as well as to gain a better understanding for how a combination of these two design space representations help facilitate spatial understanding among the participants.

Figure 2. Miniature model showcasing the building in its entirety as well as sectioning of the various floors reviewed by the participants.

3. Results

The following section presents the design errors the participants found in each respective workshop session as well as in what view-modes in BIMxplorer they were found in (i.e., the miniature model view or the 1:1 scale). These tables will then in the subsequent analyzation chapter be further discussed. This is done to see how potential patterns among the discovered design faults can be found and how these relate to the allocentric, and egocentric design space representations described in the earlier sections.

As illustrated in table 1, most of the discussion and design changes were related to changing of the space and width and height and size of the rooms and corridors in the building due to better understanding and perception of the designed space. Other changes were sightlines pertaining to the visibility between the entrance of the school and the restaurant, given that it was important for the project members to understand the logistical flow between points in the building. The participants switched between the two different view-modes (miniature model and 1:1 scale) to better understand how design issues related to logistical workflow could be addressed. The logistical workflow was critical for the project, given that the different floors and parts of the building covered different school grades and it was important to keep classes separated from each other.

Further, the project leader participating in the workshop acknowledged during the open discussion taking place after the workshop, how the sightlines between the building entrance and restaurant as well as the placement of glass portion in the various

educational rooms facing the adjacent areas were previously in 2D not apparent to them:

> "The design issues we discovered and discussed today were difficult to see let alone discuss about in the 2D drawings we have used up until now."

3.1. WORKSHOP 1

Table 1: showcasing types of design feedback and errors found during the first workshop.

Types of design feedback and errors found	Miniature model	Scale 1:1
Change related to perception of room size and space		
Disorderly placed furnishment restaurant		X
Too narrow of a serving space in the restaurant	X	X
Logistical flow in staircase between floor plans (e.g., width and landing size)	X	X
Change related to functions in studied space		
Accessibility and logistic flow connected to the counter in café/restaurant		X
Door placement and swing direction to the restaurant to be adjusted to enhance logistical flow to restaurant		X
		X
Design error: Security glassed curtainwalls and door were missing between floor 3 and 4		X
Change related to views & sightlines		
Ensured unstructured sightline between kitchen and restaurant	X	X
Glass in door between restaurant serving and tray line		X
Glass partition is missing in the teacher's room		X
Lower the sill-height of window in kitchen/office		X

A development manager also made a point about being able to discover bigger design issues at an earlier stage in the design process:

> "Rather than trying to interpret and understand design issues by myself, I would preferably be able to communicate and resolve design issues together with different actors in different phases of the design process."

Lastly, the observations showed how the first session entailed a more exploratively driven approach by the participants, where the focus was more oriented towards learning how to navigate and use the interface. Consequently, the design issues detected and addressed in the first workshop were done in a non-systematic way with three participants being in the model at the same time and using for example the interface functionality of coordinating other participants to their own location once they detected something of interest, they deemed worth discussing (left picture in figure 1).

3.2. WORKSHOP 2

Types of design feedback and errors found	Miniature model	Scale 1:1
Change related to perception of room size and space		
Window recess		X
Radiators		X
Window recess done with stone slab on top of concrete wall		X
Can windows recess be used as seating area?		X
Change related to functions in given space		
Alternative placement of water dispenser	X	X
Teachers' workplace without daylight not a viable option		X
Placement and amount of storage cabinets in teaching room	X	X
Furnishment in majority of rooms is good	X	
Worktop alongside corridor may have to be done deeper		X
Shelfs on wall in the school nurse's room must be stripped away		X
Potential inversion of furnishment in the school nurse's room	X	
Change related to sightlines		
Glass partition towards waiting area must be stripped away	X	X
Glass partition towards staff room must be stripped away → door is done with glass	X	X

Table 2: showcasing types of design feedback and errors found during the second workshop.

The VR-model used in the second workshop included furnishment, done by the interior architect. This led to an increasement in number of questions regarding logistical flow, as well as participants switching more noticeably between the different view-modes, more so than the preceding workshop.

Further, design questions pertaining to functionalities of certain rooms were more tangible in comparison to the first workshop. Specifically, questions were oriented around how functionality of classrooms could be affected by the fixed furnishment (e.g., tables and lockers). The discussion that followed revolved around the cost of maintaining the current arrangement of the fixed furniture and how it would affect workflow as well as how it could lead to increase cost over time. One example of this is when one of the development managers suggested rearranging tables in such way that it would open up space from the teacher desk, seeing as the project and facility manager experienced it as too cramped. This was an important discovery as these fixed furnishing also included sanitary piping (e.g., laboratory equipment desks), which would have been very costly to change after construction, when the building was in operation.

"We can gain more space if we push the tables in the centre of the room against the wall and thereby making it less crowded for those sitting at the edge of the room. This should lead to a better logistical flow and avoiding potential risk of conflict."

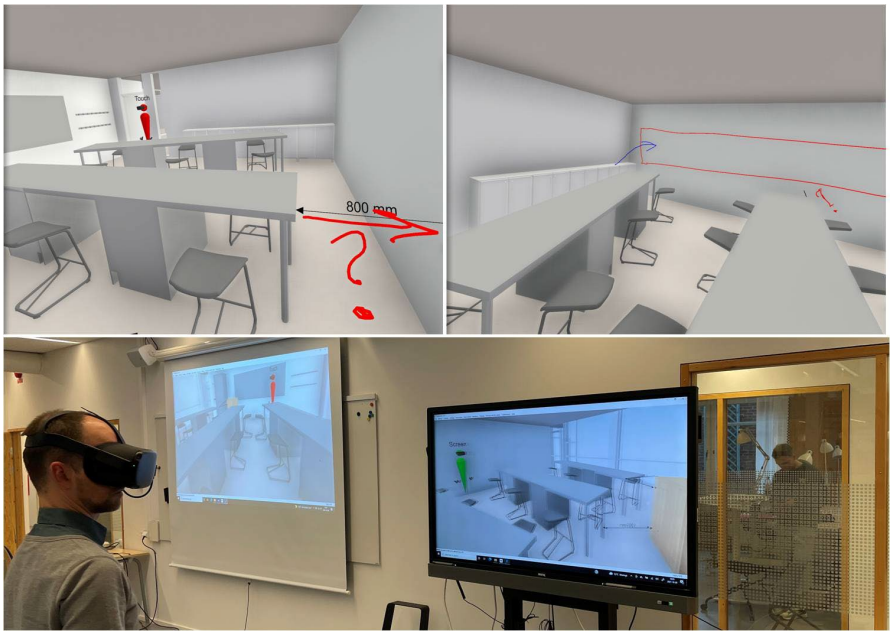

Figure 3. The development manager mentioned above, reviewing the placement of furnishment, illustrated in 1:1 and visible on the projector screen for other participants to discuss.

Lastly, it was observed how the second workshop, in comparison to the first session, entailed a more systematic approach to detecting, discussing, and addressing design issues. With the first workshop revolving around three participants simultaneously interacting and collaborating in the same VR-model, the multi-user factor shifted over to discussion revolving around one user being in the model and another participant sporadically joining in the same discussion taking place or detecting issues in a different space on the same floor, as seen in figure 2. The participants not wearing the VR-goggles were instead discussing in front of the project screen, as seen on the right picture in figure 1.

4. Discussion

4.1. DESIGN CHANGES DUE TO VR DESIGN REVIEW

The observations made in both the workshops, showed participants quickly learning how to interact with each other via the multiuser functionality as well as interacting with the model via the various tools (e.g., using the measuring tool, taking screenshots, markups etc.). The participants expressed how these features enabled them to

collaborate and understand each other's point of view and spatial reasoning in a more participatory way (Van den Berg et al., 2017) in comparison to the 2D drawings used in the project up until the point of the workshops. This common frame of reference became tangible when design changes related to the furnishment of the facility were discussed and addressed during the second workshop and could be explained by the less demanding cognitive workload apparent when using VR over 2D drawings (Dadi et al., 2014; Liu et al., 2020; Roupé et al., 2014).

Moreover, it became clear that the addition of furnishment in the models resulted in a deeper and more focused discussion around the design errors that were discovered. This also reinforces the argument presented in similar studies where furnishment and functionality related details were deemed more important than photorealism (e.g., lightning, texture of material, colour scheme in the model) in terms of enhancing spatial understanding among end-users (Abouelkhier, 2021; Mastrolembo Ventura et al., 2019; Sateei, 2021) Furthermore, our result confirms previous research in that gradual increase in level-of-detail (LOD) level should be advocated instead of photorealism. Lastly, it could be argued that the amount of design changes addressed in the first workshop in comparison to the second workshop was mainly influenced by the addition of furnishment, which is also reflected in the higher amount of design issues discovered, discussed, and addressed in the second workshop. In addition, furnishment influences the context and meaning to the space and this in turn affect the operations of the educational facility (Frelin and Grannäs (2020).

4.2. VR SUPPORTING ALLOCENTRIC AND EGOCENTRIC FRAME OF REFERENCE

Previous studies have shown that users can get disorientated in VR and that it could be difficult to understand spatial and zoning relationships (Castronovo, 2019; Liu, 2020). However, we did not see this behaviour in our study. Instead, participants mainly relied on the miniature model as a map to gain a better understanding, orientation, and overview of the facility. The instant switching between view-modes also allowed participants to explore the same design issues from both self-centered egocentric perspectives as well as environment-centred allocentric perspectives within the same medium.

This switching between the two view-modes could then argued to be supported by cues of both frames of reference in each respective view-mode. An example of this is the green-coloured arrow in the miniature model-view that supported positioning and orientation in the facility. The multi-user representation, seen as avatars in both view-modes (figure 2), also facilitated positioning and orientation which aided coordination and collaboration among the participants.

Furnishment also acted as another cue. This can be seen for example in figure 3, where discussions about furnishment and how it affected the functionality of studies space came about as a result of the interplay between the two view-modes. Moreover, it was clear that the additional furnishment influenced the participants' frame of reference in the different view-modes. Furnishment seen in the allocentric based miniature model helped participants understand what type of room it was whereas furnishment seen in the egocentric oriented 1:1 scale helped participants understand how the room worked. In other words, furnishment could be seen as an important

allocentric cue in both view-modes.

Previous research highlights and advocates the need of multiple modes of representation to support individual work as well as to support cross discipline communication during the design process (Mastrolembo Ventura et al., 2019; Roupé at al., 2019). For instance, architects sometimes have a preference to start from a more allocentric point of view (i.e., 2D drawings) before switching over to 3D and other information mediums. At the same time, building end-users often state that they "do not know how to read 2D-drawings" (Mastrolembo Ventura et al., 2019). In a similar way, the use of immersive full-scale VR during our study came as a result of the client's representatives expressing that it was difficult to get a full understanding of and review the project from 2D-drawings only. However, during the workshops the miniature model was used to a surprisingly high degree for both discussions and individual inspection. In this context, the miniature model can perhaps be seen as sort of a hybrid between a 2D-plan representation and a physical scale model, especially with the use of a section plane (Figure 2). It is then interesting to see that the representation that they didn't understand before the workshop then became the centre of attention to such a high degree during the workshop (e.g., see Figure 1, right). Still, it is somewhat unclear if it was the use of immersive, full-scale VR that made the participants better understand and relate to a (hybrid) 2D-plan representation of the project, or if the miniature model itself is a better representation in terms of project overview compared to a traditional 2D-plan. What became clear, though, was that the two view-modes were used to discuss and address different design issues. For example, logistical flow that affected the facility at large, was discussed and addressed mostly in the miniature model whereas room functionality (e.g., placement of furnishment) was primarily discussed in the 1:1 scale view-mode.

5. Conclusion

The result of this paper shows that by supporting easy switching between both egocentric and allocentric frame of reference in the same VR medium, it is possible to achieve an enhanced spatial understanding for orientation and overview of the design. Furthermore, by allowing multiple users in the same model the participants could simultaneously explore same and different view-modes, which facilitates collaboration and leaves less space for misinterpretation of the reviewed design issues. In this context it was found that the miniature-model was used more than expected considering that the main purpose with the workshops was to review the design in scale 1:1 in immersive VR. It was also found that for both view-modes the addition of furnishment greatly enhanced understanding, collaboration, and discussions among users. Furnitures bring purpose and context to the facility and therefore it becomes easier for the participants to reason about different locations and the logistical flow and also how it affected the immediate area. This observation thus highlights the importance of having a sufficient LOD for the purpose of the review. Lastly, through the integration in education, the project contributes to SDG 4. Furthermore, it also supports SDG 9, SDG 11, SDG 12 as it contributes to a more effective and sustainable design and construction process.

For future research, it would be interesting to study how LOD can be mapped to different phases of the design process and how the different phases affect cross-

discipline collaboration and the level of design issues discussed and addressed collaboratively.

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