Exploring the possibilities of using interactive virtual reality as a tool for experiencing architectural visualizations

David Mockovsky
Department of Architecture, Design and Media Technology
Aalborg University
Aalborg, Denmark
dmocko18@student.aau.dk

Oscar Bill Zhou
Department of Architecture, Design and Media Technology
Aalborg University
Aalborg, Denmark
ozhou18@student.aau.dk

Mikkel Sang Mee Baunsgaard
Department of Architecture, Design and Media Technology
Aalborg University
Aalborg, Denmark
mbauns18@student.aau.dk

Clemens Philipp Frank
Department of Architecture, Design and Media Technology
Aalborg University
Aalborg, Denmark
cfrank15@student.aau.dk

Figure 1. A picture of the virtual environment featuring the sustainable Z-house.

Abstract

Visualizing projects is a core aspect of architecture, as it presents the architect's vision of the building, but also its atmosphere. Current mediums commonly involve drawings, computer renders and scaled down physical models. The renders are often heavily edited, to the point where they can present an exaggerated and unrealistic portrayal. Furthermore, said mediums can make aspects such as communicating sense of scale difficult. Current research points towards virtual reality (VR) as a useful tool for visualizing architectural projects that enables experiencing the space through embodiment. With that in mind, we created a VR

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experience that presents a sustainable house in a nature environment. We evaluated this design on architecture students(n=14) and conducted systematic qualitative analysis of semi structured interviews in order to outline the potential use cases, strengths and weaknesses of VR in architecture. Additionally, we collected and analyzed quantitative data in the form of tracking and frame data, that correlates with the qualitative data and helps outlining design guidelines. The results showed that VR is seen as a useful tool to communicate vision, ideas and correctly understand the sense of scale and atmosphere. From this, we derive design guidelines for using VR in the architectural context, and identify potential future research topics.

Keywords: Virtual reality, Virtual environment, Interaction, Architecture, Visualization, Sense of scale, Understanding, Communication, Atmosphere, Unreal Engine 4

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1 Introduction

In architecture, it is important to visualize the work to get an idea of space, scale and the "feel of the building". This has been done in numerous ways throughout history, from the 1950's where photography and cinema were being disseminated and used as new innovative communication tools. However, by the 1960's computer aided design (CAD) was slowly being introduced and by the end of the 1980's full 3 dimensional (3D) objects were used as representation through Building Information Modeling (BIM). This allowed the user to view their model from any point and angle, which made it possible to develop a project with direct awareness of it's dimensionality. [2] These technologies continued to evolve and the level of detail is still growing ever closer to reality. Consequently, studies of how virtual reality and its potential in architecture emerged and are getting more prominent, having the potential to become one of the new tools for communicating architectural understanding.

1.1 Architecture's current practices and limitations

As technology continues to evolve, so does the extend of what can be disseminated from an architect's own internal vision. Furthermore, there is an ongoing discussion within the field of architecture about the possible misrepresentations of projects, due to the tendency of editing renders with an artistic interpretation [7] [15] [14] [5]. According to Degen et al. [3], this tendency stems from the market requirements, or "experience economy", and the loss of artistic expression after architects moved from drawn images to computer generated images (CGI). In their ethnographic study they followed the visualization and illustration practices of architects and illustrators during a redevelopment project in Qatar. The architectural language advisor hired for the project specified certain design guidelines for illustrations, with a crucial one being to

> *"(...) depict a 'Memorable Moment': the CGI should be 'a slice of life which carries a story and also a resonance'; certain items or events add integrity to the picture such as a bike, blurred, in motion, or a child, running or smiling, towards the camera."[3]*

This tendency is due to the limitations of the medium, as the main purpose is to convey the designer's internal vision, which can be difficult to represent in a render. To alleviate this, they modify either the atmosphere or model of the render, thereby creating a more idealized version of the vision. This stems from a multitude of standpoints. Firstly, from a commercial standpoint, architects are dependent on clients to purchase their product. Secondly, architects want to convey a certain mood or feeling. However, what started as a means to make renders look prettier by insinuating certain associations with the building (e.g. inserting a happy family or making the weather perfect [7]), has slowly become a genuine concern. That is due to the unauthentic representation, which can lead to miscommunication, where in some cases the buildings themselves have been edited to some capacity. This is what some architects would consider crossing the line, as they are misrepresenting the actual architecture. One way to circumvent this is to change the medium all together, focusing instead on a more embodied approach. As stated by Daniel Libeskind in an article by Azure Magazine:

> *"Photography has helped architecture in the sense that it has made buildings look better than they really are," says Libeskind. "But while a striking image may be a brilliant way to market a project, it also fundamentally cannot capture the experience of visiting a building [7]."*

1.2 Virtual Reality and its current use in Architecture

One medium which could afford the experience of visiting a building is virtual reality (VR), since it offers an embodied experience, allowing users be present within a 3D environment, going away from renders and focusing on a real-time experience instead.

Morse et al. investigated this notion, using VR within a modern day game engine, to create an interactive 3D experience [11]. He investigated the use of a game engine, a real-time software development environment, to create experiences for architecture, since it affords interaction and dynamic lighting. He further states that by interfacing with the game engines through VR, one can curate virtual tours, which can be a powerful spatial visualization tool [11]. This could serve as a means to enable designers to become more transparent in their communication with contractors in the design process, create new methods for architectural education to represent models, and circumvent possible misunderstandings. This paper serves as an outline of the potential that both game engines and VR could offer.

Investigating said design process, Hsu et al. [6] researched the potential of using VR in the current architecture practice, by developing a VR experience in a game engine, in order to create a more effective medium for communicating ideas. The current practice uses 2 dimensional (2D) drawings to conceptualize ideas which is a fast and easy approach, however, this requires a higher mental effort due to its limited nature. Another approach using physical models is more visual and spatial, however, they are more costly and less flexible to iterate upon during design sessions [6]. Furthermore, said sessions usually rely on physical attendance, which can be a time consuming task to coordinate. Thus, they created a VR experience to solve the issues of current practices, similarly to what Morse et al. outlined in his paper [11]. The experience included interactions which allowed to create objects and modify them. It also allowed for multiple people to be present in the same scene. The purpose was to create a more visual way of communication, which they tested on a shared experience with students, teachers and experts. Though without any clear findings, they suggest that the experience could be effective to support an architectural design discussion [6].

Overall, the research suggests that using VR within architecture can be a promising means to communicate ideas, as opposed to the current practice, especially by using a game-engine, since it offers real-time control of the environment and lighting.

Other notable paper that researched this area is by Khavari et al. [8], who suggest that VR can increase spatial knowledge of a student through interactions, which could be used in architectural education to increase engagement and motivation.

Further, Ozacar et al. [12] investigated using VR to create a lightweight experience for customers to explore a building before investing in the property, affording teleportation and changing of texture in real-time.

Though all aforementioned research focus on integrating VR into the architecture practice, very few put emphasis on explaining the evaluation, while some completely omitting it. Nonetheless, one of the main attributes of VR is it's spatial influences with a sense of scale superior compared to a 2D medium. Furthermore, it is important to understand what contributes to the sense of scale while also considering the possible drawbacks.

1.3 Perceived distance in Virtual Reality

Masnadi et al. claims that multiple factors of a head-mounted display (HMD) can affect the perceived distance in VR, stating that the weight and inertia contributes to distance underestimation [17]. They found a significant difference in horizontal field of view (hFOV), showing lesser distance underestimation with a higher hFOV. On the contrary, there was no significant difference between high (110°) and low (35°) vertical FOV (vFOV). Furthermore, Wu et al. found that increasing both FOVs in the real world increases distance perception [18].

Lastly, Masnadi et al. [17] found a significant difference in distance underestimation between a cluttered environment compared to an uncluttered environment, i.e. it is easier to underestimate distance in an empty virtual room compared to a room filled with objects such as furniture. On the same note, Kunz et al. and Vaziri et al. found that the graphical level of a VE is important for distance judgment, suggesting the overall level of detail in a VE contributes to accurate spatial representation of architecture [1] [9].

These papers suggests that VR has a tendency to make the user's underestimate distances in general. However, this can be mitigated by a lighter HMD, higher hFOV and more objects within a scene.

To summarize the presented work, VR has the potential to be the next iteration of architecture visualization. Since much of the research focuses on a technical evaluation, or has inconclusive findings, it is unsure where exactly VR could fit on the architecture pipeline and the specific usecases. Therefore, this paper will focus on exploring the benefits and shortcomings of VR when it comes to communicating the correct understanding of the architect's vision, as well as how it fits into the idyllic and photorealistic debate.

2 Design of the prototype

The prototype was made in Unreal Engine 4 (UE4) [4]. The architectural 3D models used for the project were supplied by Marwa Dabaieh, Associate Professor from Malmø University [1], who owns the rights to the project idea, designs and drawings. The models were slightly altered for performance and aesthetic optimization using the 3D modeling tool Blender [2] and then imported into UE4. Additional assets

[1] Malmö University, Department of Urban Studies - Unit of Built Environment, https://mau.se/en/persons/marwa.dabaieh/
[2] https://www.blender.org/

Figure 2. A render of the Z-house made and provided by Marwa Dabaieh.

came from the Unreal asset store [3] or were created for the purposes of this project.

The general aesthetic of the VE was partially inspired by existing 2D renders supplied by Marwa Dabaieh, giving the VE stylistic lighting evoking a warm summer day. For comparison, one of the supplied renders can be seen in Figure 2, and Figure 1 shows our interpretation in the VE. Additionally, sound queues of birds chirping, wind blowing and leaves moving were present in the scene.

2.1 Promoting exploration within the virtual environment

We designed the prototype to fit a narrative of sustainable housing with the focus of exploring the unique sustainable systems of the house. The forest setting of the environment was chosen to promote connectedness to nature. To make the users explore different aspects of the house, a blackboard was put on the front porch of the house in the user's start location, asking them to complete three separate tasks:

1. Pull up the fridge.
2. Close the ventilation.
3. Open the blinds.

The task instructions were intentionally brief to encourage exploration. The layout of the tasks, starting location and placement of the user interface (UI) elements can be seen in Figure 3.

2.2 Displaying information with UI elements

Furthermore, a non-diegetic text widget (2D plane with text) was placed on top of the blackboard, welcoming the user and giving them general information about the house. Additionally, another widget was "attached" to the user's left controller which would vibrate upon completion of each task and provide the user with information about energy consumption related to the current task.

[3]https://www.unrealengine.com/marketplace/en-US/store

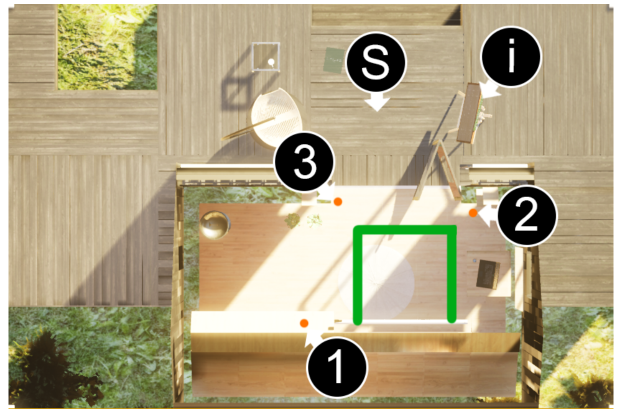

Figure 3. Top view of the house, with numbers corresponding to each task in order. The precise location of each task is highlighted with a red dot. The "*S*" is the starting position, with the arrow being the gaze direction. The "*i*" is the position of the UI elements, being the blackboard and the starting widget. The green outline shows the position of the bed if extended from the wall.

2.3 Interaction within the VE

As suggested by the research within VR, interaction within a 3D environment can afford an experience which could increase motivation, engagement and spatial knowledge [6, 8, 11, 12]. With this in mind, the following interactions were included in the simulation. Movement is afforded through real world locomotion, but the user has the option use teleportation using a controller. In the latter case, the *A* button on the Quest 2 controller can be held down, which projects the destination, and upon release teleports the user. It is important to note, that the connection between the headset and computer is tethered, therefore the physical movement is limited to the cord length. The user can pick up certain items in the scene, such as coffee mugs, cereal cans and soda cans, which are placed around the house, either on tables or in cabinets which could also be opened. The user can pull two strings, which would open either the ventilation or the blinds. Further, a rotating crank can be interacted with to pull up the fridge. The interactable objects related to the tasks, such as a handle, were highlighted with a red outline to signify the current task. The remaining interactions did not include an outline, so they are not confused with the tasks and to be more diegetic. Lastly, the user could push two hanging plants, which would respond accordingly with physics, resembling the behavior of a pendulum.

2.4 Graphics and performance

When it comes to graphics design, we wanted to achieve as realistic graphics as we could given the assets, time-frame and hardware limitations. The minimum acceptable frame rate we aimed for was 30 frames per second (FPS). Most optimization work consisted of simplifying and retopologizing the provided models in Blender. In terms of global illumination, we used Unreal's surface and volumetric lightmaps. For performance reasons, the lightmap resolution had to be limited. Further, while dynamic time of day might be desirable in architectural visualisations, we opted for just static lighting. If time of day is desired, one can potentially interpolate between different lightmaps. This, however, requires even more texture memory. A skydome provides additional ambient atmospheric lighting and Unreal's atmosphere system takes care of atmospheric scattering.

3 Experimental design

3.1 Iterations

The prototype was first tested for usability with four Medialogy students from Aalborg University (AAU). This was done to improve on the initial design and fix potential errors or design flaws that have been overlooked. Upon fixing issues that were uncovered by the usability test, which are described in detail in the Worksheet [Section 4.7], the prototype was tested on architecture students. In this paper, only the second round of testing and its results will be presented.

3.2 Participants

The participants (n=14) were recruited based on their study degree and only students from the Architecture & Design degree from AAU were selected. There was an even split between bachelor and master students.

3.3 Apparatus

The testing was conducted in two lecture rooms at the CREATE AAU building, with available unobstructed space of approximately 5x7m. The test was conducted using a Lenovo Legion 5 laptop, with an AMD Ryzen 5 CPU and Nvidia GeForce 3070 laptop. The laptop was connected to a Quest 2 HMD, described in detail in the Worksheet [Section 4.1], with a 4 m tethered connection.

A logging script was used within the program, which saved the framerate, X, Y and Z position and rotation of the headset within the scene, as well as the current task and timestamps.

An additional laptop was used to complete the IPQ questionnaire. A camera was used to record the gameplay.

3.3.1 Procedure. Two test conductors present, one for handling the program and its setup including the headset, and the other for organizing the experiment. Each participant had to sign a GDPR consent form, agreeing to the accumulation of data, prior to the experiment. Once signed, they were introduced to the control-scheme of the VR-application and brought into the simulation. The program footage, as well as the outside-view footage was recorded for every participant. Within VR, the participant had to complete three tasks and were encouraged to explore the house. Furthermore, once finished with the tasks, they were asked to observe the house with the perspective of an architect, viewing it like they would view a model in their traditionally preferred program, and they could leave the simulation at anytime they thought they had seen enough. This was followed with an the IGroup Presence Questionnaire (IPQ) to measure the participant's presence within the VE. Additionally, a recorded semi-structured interview was conducted, allowing the user to elaborate on their experience within the VE from a general and architectural perspective. The layout of the testing can be seen in Figure 5.

3.4 Analysis of the data

The data gathered from the experiments consists of qualitative and quantitative data, which will be explained below.

3.4.1 Qualitative data analysis. The raw audio recordings from the interviews were transcribed via Otter.ai [16], a real time transcription tool, and manually corrected. Afterwards, the interviews were analyzed for themes by two independent teams doing open coding associating new codes with each snippet. One team worked in Excel, the other used the qualitative analysis tool Delve [10] This was followed by a discussion and axial coding, i.e. finding parallels and overarching themes that put different excerpts in perspective.

Before continuing to define the core findings through selective coding, this process was repeated with a new round of participants to see whether any new themes would emerge.

Further axial and selective coding was then carried out within the two teams again. One team continuing with an inductive approach while the other team conducted selective coding deductively taking previous research and prevailing ideas as a starting point.

Finally, both teams reconciled to compare and merge findings. Communication and understanding were identified as the prevailing theme most other themes were subsidiary to.

3.4.2 Quantitative data analysis. All the quantitative data from the logging and IPQ, was analyzed and visualized in R-studio [13]. The findings of which will be presented in results, with the exception of IPQ. This can be found in the worksheet in Section (REF).

4 Results

This section first presents the results of quantitative data gathered from the logger and continues with presenting the results from qualitative data analysis. The latter includes emergent theories, where Figure 6 shows how the themes of the subsections relate to each other.

4.1 Framerate

The framerate for each participant can be seen in Figure 7. Though all participants had above 30 FPS experience, which

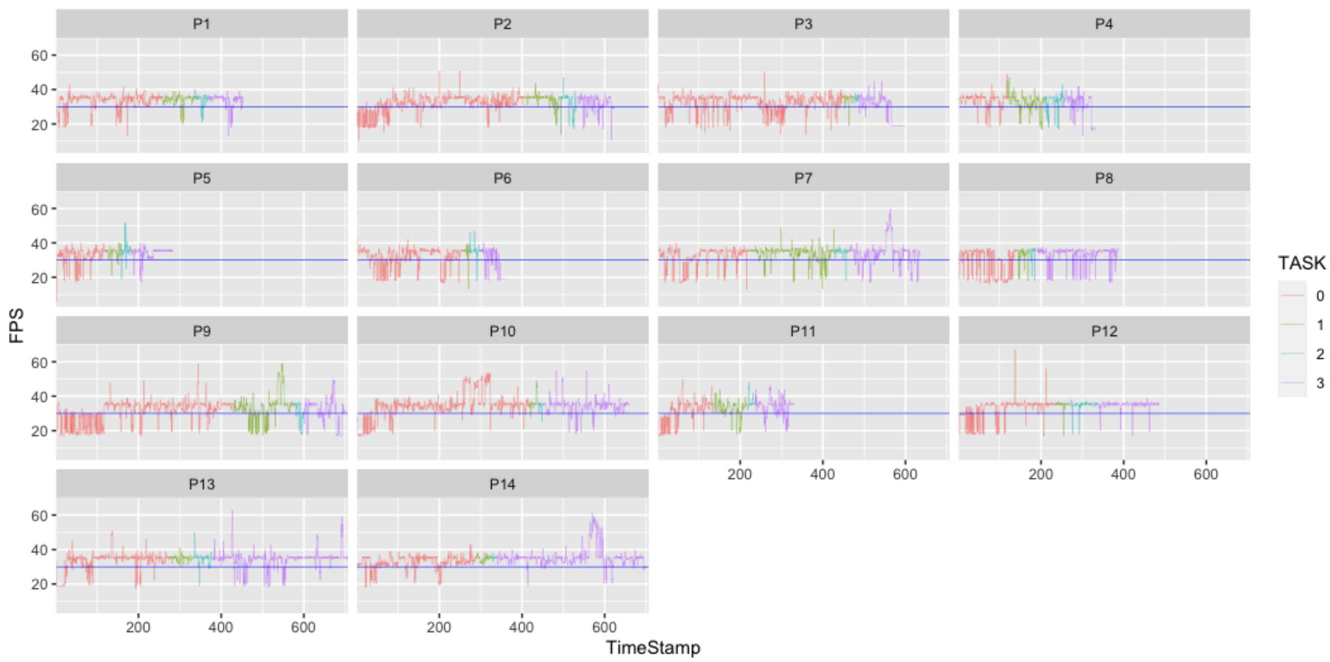

Figure 4. This Figure shows the tracked framerate of the participants throughout the experience, with one graph for each participant. The colors differentiate between the tasks, with red (0) being from the start until completion of the first task, green (1) until completion of the second task, blue (2) until the third, and purple (3) for the time they spent exploring after completing the last task. The Y axis is in seconds and the blue line is a threshold of 30FPS.

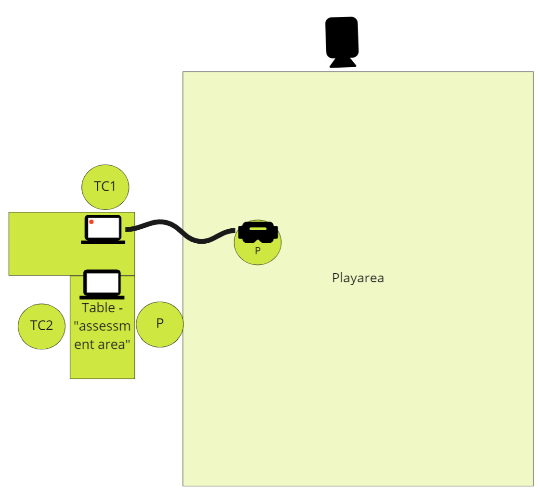

Figure 5. The figure shows the setup of the testing. *TC1* and *TC2* represent the Test Conductors, and the *P* represents the Participant.

is what we considered acceptable, their graphs show substantial variance. The mean and variance of the FPS for each participant can be seen in Table 1.

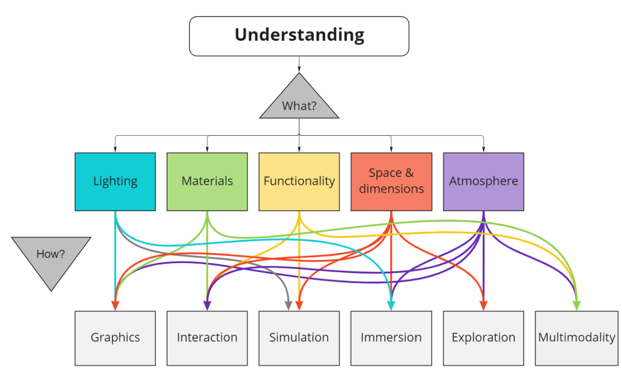

Figure 6. This Figure shows how the different topics relate to each other, while all contributing to an overarching theme of *Understanding*.

4.2 Position

The spatial movement within the house for each participant is shown in Figure 7. Close proximity between the dots, such as with P1, indicates that the participant preferred physical movement, while larger discontinuities, as with P2, mean that the participant used the teleporting feature. The Figure also shows that 9 of the 14 participants (P2, P4, P5, P6, P7, P9, P11, P12, P13) explored the exterior of the house (not

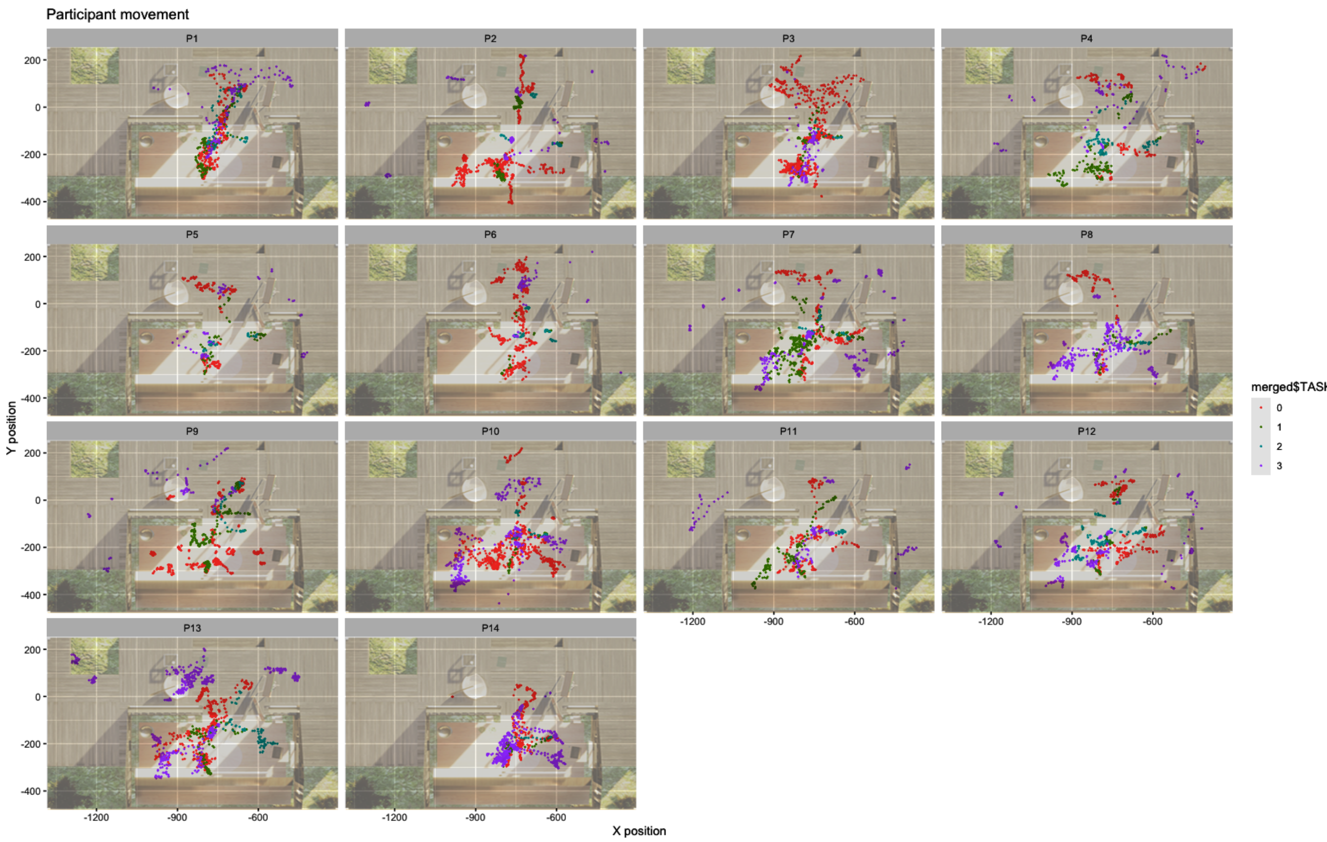

Figure 7. This Figure shows the tracked positions of the participants throughout the experience, displayed from top view, with one graph per participant. The colors differentiate between the tasks, with red (0) being from the start until completion of the first task, green (1) until completion of the second task, blue (2) until the third, and purple (3) for the time they spent exploring after completing the last task.

	Mean	Variance
P1	33.63544	14.00367
P2	32.15937	24.79193
P3	31.97950	27.99958
P4	32.58398	27.95320
P5	33.50271	19.04030
P6	31.75641	34.27867
P7	33.22823	30.27636
P8	31.41114	42.27961
P9	31.62381	49.05356
P10	34.32583	37.15928
P11	32.58075	35.58756
P12	33.58098	23.89014
P13	34.10895	23.27693
P14	34.50585	21.14115

Table 1. The FPS statistics, including mean and variance for each participant across all tasks.

counting the starting location area), moving or teleporting around it. All of them did this after finishing the tasks, as indicated by the purple color. 10 of the participants explored the interior of the house beyond the locations of the three tasks. From these, P8, P12, P13, P14 explored after completing the tasks, while P2, P4, P7, P9, P10, P11, did so during the tasks.

4.3 General Response and Use Case Results

In general, participants reported a feeling of immersion and presence, great sense of scale and space, understanding of the house and perceived emotional affect. This corresponds to existing research and prevailing ideas of why VR is useful for architectural visualization.

The participants mentioned different possible use cases for VR in their studies and projects, with most having similar reasoning for the proposed practice. 13 out of 14 participants expressed a desire to use VR as a tool specifically in order to facilitate better understanding and communication of architectural design to others. The reasoning for wanting to use VR for communication practices was to prevent miscommunication and providing other people with a greater understanding of their projects and ideas due to the various affordances of VR, which will be discussed later.

> *"It creates this conflict between client, architect and construction, like when they miscommunicate. They can take a tour in this house and see how it's supposed to be. [...] There might be less mistakes. Because it's presented more precisely."*

The participants expressed a desire to employ VR throughout the entire architectural pipeline, from initial designs, where it could provide better understanding for the designer, through mid-term collaboration with peers, teachers or other stakeholders, to final presentation of the vision.

> *"I'm just excited, I want to use this in the design process and to present my products to really eliminate confusions and misunderstandings between the client and the designer."*

> *"I think it can be used for educational purpose. And also it can be super useful when you have a customer and you have to design a building."*

Additionally, architecture students wanted to use VR in a usability testing capacity, for which VR has been widely adapted in other disciplines. This approach might potentially allow for more drastic or experimental design in architecture.

> *"We imagine how they use it, but it's not always how they would use it. So maybe VR could be a way to learn about user behavior"*

4.4 Understanding and communication goals

Understanding and communication were present throughout the whole findings and can be seen as the main strength VR provides in the architectural pipeline, which corresponds to the findings by Morse et al. [11] mentioned in Section 1. The participants consider VR as a tool that can better communicate the following aspects:

1. Spatial understanding,
2. Atmosphere and emotional affect,
3. Visuals and lighting,
4. Materials,
5. Functionality

4.4.1 Spatial Understanding. One of the most prevalent reasons participants gave for why they would want to use VR in their studies and work was the spatial understanding afforded by VR. Apart from the purely technical aspects like the one-to-one scale, greater field of view, or sense of depth, there were a few other reasons uncovered in relation to the spatial understanding. Some participants mentioned that they felt like their spatial understanding benefited from the ability to interact with the house and objects within it. The presence and interaction with small objects, such as a mug, also increased their sense of space and scale, which might be due to familiarity with the real counterpart of these objects.

> *"The detail and the way you could interact with the place, you can get a sense of scale, on a more precise level than in the CAD programs we're used to because you have this sense of being there."*

> *"I use the CAD programs for 3d modeling. And it gives an idea of how it looks, but it's hard to get an actual idea of of how big it is. The dimensions are much clearer once you're in the virtual reality."*

Further, free navigation and being allowed to chose your own perspective also played a crucial role when participants explained their perceived sense of scale.

> *"It was amazing that a virtual world could make such sense of space. [...] When I walked around with the different roof heights, I could feel how it actually feels to be in rooms with different heights."*

4.4.2 Atmosphere and Emotional Affect. The interviews and data also coincides with the notion that there are more things than scale, function and technicalities architects want to convey. As described by Degen et al.[3], architectural visualization attempts to "tell a story" and get the viewer emotionally involved to make it easier to imagine being in the presented place. [3] This is supported by our findings, where the participants talked about the importance of creating a specific mood, vibe or atmosphere to their visualizations.

> *"We are trying to sell an experience or a mood in some way [...] [later about the VE] this is similar to the feeling we are trying to get"*

After experiencing our VE, participants were generally astonished how immersed and "connected to nature" they felt. Further, the multimodality through diegetic sound and interaction, together with the natural environment the house was placed in creates a more holistic experience that communicates the remoteness and lifestyle. Further, sound and interaction seems to lead to better immersion and emotional affect. This in turn suggests that the immersion and embodiment experienced in VR plays a key role in creating emotional affect and atmosphere, compared to traditional renders that need to apply a lot of post processing to convey these aspects.

> *"VR Could be better, when I hear the birds and the wind it wants me to feel something, [...] be connected with the nature in this case. So it does give me of kind of a mood."*

> *"I mean I got kind of relaxed vibes, like you're alone in nature in some kind of hut somewhere. I'm disconnected from from the city."*
> *"That people don't just look but also act. It makes it more memorable and it creates more impact"*

At the same time, our scene also portrayed an idealistic scenario, including a sunny day in the middle of the forest, with birds chirping and visual bloom and fog to create a specific atmosphere.

> *"I think it was nice. It really was a little idealistic. But that is often something that we do in architecture. So I see the reason why"*

4.4.3 Visuals and lighting. Although we made a few compromises in the photorealism and accuracy of the lighting and shading for the sake of performance, it was mostly perceived as very realistic.

> *"I felt sucked into a virtual world [...] the lightning was almost like a real world, but with filters on it. So you put the cherry on top"*

However, some participants have noticed imperfections in the visuals, or expressed their subjective preference towards it.

> *"I think the visuals were slightly overexposed, I felt it was a little bright."*

While some participants perceived the visuals as somewhat idealized, others felt like they wanted to tweak it more to fit their expectations from rendered architectural visualizations.

> *"The lightning it was almost like a real world, but with filters on it."*

> *"Jazz it up a little bit. Flowers, Photoshop kind of lighting."*

4.4.4 Materials. In terms of materials, students were happy with the general look and found it positive that you could see these materials in different illuminations and from different proximity. They consider the visual perception of materials in VR to communicate the materials and their purpose to a degree, but still preferring renders. On the other hand, the main concern was that VR did not provide any haptic feedback.

> *"You can really get close to the material and you cannot feel the tactility, but you can get so close that you can see [...] the depth in the material a bit more"*

> *"You could use it in a lot of phases, in the detailing phase where you detail the materials, you cannot feel the textures, of course, but you can see the textures."*

> *"Because, for example, the I think the the quality of rendering can be much higher than the VR in the sense of if you really want to go into materiality."*

4.4.5 Functionality. The interactivity and simulation capabilities of VR offers the ability of presenting functionality while experiencing the environment and thus creating a more holistic understanding of the architecture project. In this case, some of the functionality was presented by moving arrows, which were well perceived by all participants and clearly communicated the purpose of the systems.

> *"The simulation you had where the air goes in and out. It's very nice to see."*

> *"I did like the arrows of the ventilation, it's very clear. Same with the solar."*

Similarly, most architecture students appreciated the ability to open and close cabinets and bathroom doors, to see how the spatial design would function in real life situations. One participant went as far as to get into the bathroom, close the doors and experience it from there, which can bee seen in Figure 8.

> *"I think the hidden toilet when I walked inside it and tried to close it... Because of the window it had like a cozy feeling. And I liked that [...] Because if I drew such a small toilet, myself, I would imagine that it would be too small, very enclosed, but it didn't feel like it."*

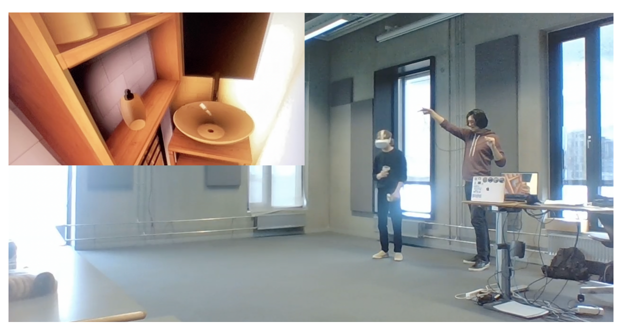

Figure 8. Participant 12 in the bathroom.

4.4.6 Information and learning outcome. Participants rarely engaged with the user interface (UI) elements in the form of widgets, that presented information about the house and it's functions. We argue that the novelty of VR, its visuals, interactions and subsequent immersion can be too big of a distraction and deter from any desire to read. However, unfamiliarity with the controls, environment and the tasks can overwhelm the participant and also contribute to this effect. At the same time, a lot of participants were simply not aware of the information widget attached to their left hand controller. When asking participants whether they noticed the widget one participants response stood out:

> *"I mean, I could see (the widget) [...] but i thought if I should read it, you will let me know."*

This may have been a fault in our briefing of participants and we could have informed them about the ways this simulation will communicate with them. This leads us to believe that a more hands on guidance may be required in these VEs, examples of which will be discussed later.

Further, while the starting widget got noticed much more than the one attached to the controller, the participants either did not read the text on it, or simply did not remember the content of it.

That being said, most of the participants understood the workings of the presented systems and their purpose, as well as the purpose of the house in general. This suggests that while textual information can hardly be completely avoided if one intents to convey complex information, visual presentation in combination with interaction can in some cases facilitate sufficient understanding and learning outcome.

5 Discussion

Here, we discuss the results presented in the previous section, following the same order.

5.1 Framerate discussion

Considering the FPS discussed in Subsecton 4.1 and Figure 4, it is clear that there is considerable variation in the FPS experienced during the testing. While overall lower FPS right after starting the program is common and improves after some time, the time it takes for the improvement varies as well.

Lower FPS can be experienced in the beginning due to the program loading the level and assets within it, and improves when the loading is done. This usually happens after restarting UE4, which corresponds to P9, being the first participant in the second day of testing.

Another reason is taking off the headset, which happened for adjustment of the straps to better fit the participant, and because of technical difficulties such as not seeing the scene. Both of these were extensive with P2 and P9.

However, the spikes during the rest of the gameplay, both in positive and negative direction, seem to be completely random and greatly vary in frequency and time of occurrence. Therefore, it seems that there is no apparent aspect that could be the cause of these spikes.

5.2 Position discussion

The results presented in Subsection 4.2 and in Figure 7 show great variety in movement of each participant. This is mostly dependent on two factors, being prior experience with VR and length of the cable during the testing.

The former is clearly visible with P5, as that is the only participant with extensive VR experience, and is also the one that used teleporting the most, spent the least time in the program and only moved around the positions of the tasks. Similarly, P4 and P6 had moderate VR experience and showed much higher usage, confidence and competence with teleporting. This can be contrasted with participants with none or low experience, such as P1, P3, P8, P10 or P14 that exclusively moved around physically.

The latter, being the length of the cable, seemed to be the deciding factor between the movement modalities for the rest of the participants. While they seemed to prefer physical movement, when they reached the full length of cable they used teleportation to close the distance to the place out of reach. This can clearly be seen with every participant that explored the house from outside (P2, P4, P5, P6, P7, P9, P11, P12, P13), which was beyond the reach of the cable.

Further, while exploration of the exterior seems to be exclusive to after being done with the tasks, it differs for the interior. Here, P2, P9, P10 and partly P12 explored the house before completing the first task, suggesting having difficulties finding the fridge. P4, P7, and P11 show similar behavior with the second task, while P12 and P13 behave alike during the third task.

Lastly, we argue for immersion and presence, based on the fact that the participants avoided purposefully moving through the virtual walls and objects. An example of this is avoiding the bed, which can be seen with P1, P3, P5, P6, P7, P8, P11 and P13. The position of the bed within the house, when extended, can be seen in Figure 3. The participants can also be observed avoiding the virtual cabinets, the table at the right wall, the blackboard or the coffee table outside.

5.3 Derived Design Guidelines

Given the architectural communication goals which are spacial understanding, emotional affect and atmosphere, Materials, Lighting, and Functionality, the key aspects that should be emphasized during VR development for architectural visualization are: graphical realism, multimodality, interactability. As well as how to guide the user through the information dense environment, making sure that important systems are disseminated, while still allowing for free exploration.

5.3.1 Graphics. While graphics were deemed important and every participant agreed that great focus should be given towards reaching photo-realism, it is important to balance the graphics and performance. In our case, aspects such as richness of environment, additional post-processing, resolution of textures or amount of objects had to be reduced to favor smooth framerate as documented in Figure 4. For example, our VE employed dynamic objects in combination with baked indirect lighting. Due to the resolution of our Volumetric lightmap, some artifacts could be observed when deliberately looking for them. However, these trade-offs did not seem to bother participants, as they felt the lighting achieved sufficient realism and atmospheric understanding of the space. More focused research could investigate how accurate lighting has to be before it impacts sense of scale, emotional affect or other communication goals.

Materials are another important aspects regarding graphical accuracy. While our materials where generally perceived as visually compelling, we did not use any overhead shader instructions or costly post processing effects such as real-time reflections, subsurface scattering or even simpler ones such as normal maps. This was only once reflected by a participants comment.

> *"They kind of had that clay feel to it, where you can tell that it's not quite real"*

For final development, normal, detail and smoothness maps should be considered an important asset for making materials look more realistic while not impacting performance all too much.

5.3.2 Multimodality and Interaction. Multimodality in the form of sound, visuals and written or spoken words is important for conveying the ambiance and vision of architects. Specifically, diegetic sound seems to lead to better immersion and emotional affect. Overall, visual information was received positively i.e. the arrows symbolizing airflow appears to be a great tool to communicate the functionality of the building as VR has limitations in terms of human senses i.e. our findings suggests that the lack of sensual representations can be substituted with visual animations to better understand a buildings functionalities.

Interaction is also important for engagement and immersion, as participants were observed to play around and try to pick up every object they could find. Interaction serves as a corner stone in participants accounts of discussion points and thus may facilitate discussion, if the participants were stating something in the category of: If I did this, I felt that" and participant 10 specifically stating: *"when I closed the bathroom door I felt it was spacious enough"* Furthermore, text explaining the functionalities in VR could have a tendency to be ignored if the system affords interactability and movement. However, the outcome could be different if a system did not have these affordances.
Overall, VR affords more modalities than the traditional tools currently used in architecture, which opens new windows that can be taken advantages of when it comes to communicating the desired understanding between architect and client.

5.4 Future research

5.4.1 Guided vs free exploration. An additional possibility is to use a more guided approach to convey this type of information. While previously mentioned visual representations are still possible in VR, a virtual guide explaining the meaning and systems directly while still visualizing quantities and function could benefit understanding and retention, similar to existing research in VR as an educational tool in other areas. VR can be an overwhelming experience, especially for first time users, and this could take away from the attention a user has for the systems the designer would want to focus on. While this should not impact VR incorporated into design processes, future research could investigate how to best disseminate technical information for visualization purposes within a holistic architectural VE. Possibilities could range from simple UIs with more guiding elements to co-experienced guided tours with the architect. It is important to note that a possibility could be to sacrifice some immersion in order to have the architect speak to the client while they are in the VE to insure correct understanding of the architecture is taking place.

5.5 VR for architectural education

The astonishment about the affordances of VR from the interviewed students points heavily towards the potential VR has as an educational tool for architecture students. Many participants mentioned directly or indirectly that they could learn a great deal from Virtual reality. As such VR could help them develop their initial sense of architectural fundamentals quicker in a more proactive way. Students could be prototyping buildings, shapes and play with materials in an immersive environment rather than learning from theory. Instead of inspecting other peoples designs that have been build in the real world they could become active participants in their own learning process.
Some current obstacles for inclusion of VR in every day architecture practice are required expertise and hardware. However, Universities could have these at hand and cross faculty coordination could make these systems available for architecture students. If formal education adopts these new practices, with time they could become widely used in the industry. Additionally game engines such as Unreal or Unity are always advancing, becoming more beginner friendly with features such as visual programming languages, project templates including dedicated architecture and VR templates as well as simplified all around lighting solutions that do not require extended expertise for basic use. Another issue common when trying to move architectural models into a real time interactive experience tends to be the complexity of 3D objects that are not designed and optimized for real time

use. During the implementation of this project 3D models had to be manipulated, polygon reduced and cleaned up in Blender. Here, Unreal engine 5 could potentially provide a game changer with its Nanite system for automatic polygon reduction and vertex culling. On the other hand, the current architectural modelling practices would have to change where a balance between detail and performance would have to be struck as the two domains merge.

5.6 VR in relation to the debate about realism and idealization of architectural visualization

As previously stated, the line between an reality and idyllic fiction is getting blurred, where current trends tends to over edit renders. This could be due to the limitations of the medium and how the architect in question would exaggerate to communicate their vision to the client. With VR, our findings suggests that the exaggeration can be avoided as the new affordances can compensate for it. Inherently, VR is an immersive medium which gives the users the feeling of being present in the environment where they can get the sense of the spatial dimensionality the architect had in mind. Additionally, the medium affords sounds and interactability, which further immerses the user and these interactions can create what seems like mundane yet memorable moments as talked about by Degen et al. [3] This would mean VR potentially does not have to rely on heavy visual editing to give the right mood or feeling the architecture had in mind. That being said, it still affords the abilities to do so, where game engines such as UE4 have the in-build tools to accomplish this, perhaps new ways of portraying the architects vision could be explored in VR, as a game engines has affordances renders do not, such as video, ai, animation, voice acted characters and much more.

6 Conclusion

This paper investigated the use of VR in an architectural context, aiming to facilitate a better understanding of its usecase in the field. For this purpose we presented a VR visualisation of an architectural design to Bsc. and Msc. students (n=14) of Architecture at Aalborg University. Through systematic qualitative analysis we corroborate the perceived strengths of VR and contextualize them with the architectural visualization goals and concepts as portrait by the students.

In general, participants were eager to use VR in their work not only to communicate their ideas to others, but also to deepen their own understanding of space and encourage experimentation within their studies. This suggest that VR could be an alternative to the current practices, due to its strengths regarding spatial understanding, emotional affect, visuals and lighting representation, materials, and functionality. From our qualitative data we synthesized rough design guidelines concerning graphics, interactivity, mutlimodality, simulation and hardware in order to facilitate these benefits. While these should not be taken as final, they might serve as a stepping stone to better understand the needs of architecture students and bridge the communication gap that seems to be currently present.

Finally we discuss three possible directions for future research:

1. Future research should investigate whether VR can create memorable experiences, atmosphere and emotional affect in line with architect's vision while still providing an honest representation of the product.
2. How can VR be incorporated into architectural education.
3. How to best guide the clients through an information dense VR experience of architectural design.

At the same time, it is important to consider both advantages and disadvantages of using VR and whether it is a suitable tool for the given project.

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