Real-Time Visibility Assessment in an Interactive Immersive Virtual Reality Application for Urban Public Space Design

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Abstract

The design of urban public spaces (UPSs) aims to facilitate users’ physical and mental well-being by facilitating dynamic and stationary activities. The success of a UPS is often measured by its users’ engagement and experiences. However, UPSs frequently exhibit varying usage patterns, with some areas being heavily frequented and others neglected. This discrepancy is often due to users’ perceptions of safety, comfort, and liveliness. Failure to anticipate and address these aspects during the design phase of UPSs can result in dysfunctional urban spaces that fail to meet users’ needs. People experience UPSs primarily through their senses, with vision being the predominant sense and key to spatial cognition in UPSs. Therefore, adequate visibility of the spatial configuration must be integral to UPS design as a design goal. As a result of recent advances in Immersive Virtual Reality (IVR) end-users can participate in, interact and experience the possible UPS design scenarios, however, most IVR applications do not provide real-time feedback for design goals such as visibility. Established methods exist for analyzing visibility in UPS. However, these techniques are not usually integrated into VR apps to assess the effects of the designs. This paper addresses the gap for the lack of real-time visibility feedback within IVR applications for UPS design and its technical challenge. Building on a previous IVR application, CoHeSIVE, which was developed for UPS design, we integrated a ray-casting method and Unity’s built-in callbacks for dynamic visibility assessment of the features within the user’s field of view. The visibility assessment is then presented on a dashboard within the IVR app. This study serves as a cornerstone for future real-time feedback mechanisms of visibility assessment within IVR applications for urban design, facilitating informed design decisions.

1. Introduction

This section first introduces the research background from an interdisciplinary perspective of urban design, cognitive science, and GIScience. Following that, the research aim of this study is formulated.

1.1 Research Background

The design of urban public spaces (UPSs) aims to facilitate the physical and mental well-being of UPS users through creating venues for both dynamic (i.e., walking) and stationary activities (i.e., sitting, watching) (Jalaladdini and Oktay, 2012). The success of a UPS is often measured by how people use and experience it (Mehta, 2014). When examined, UPSs unveil certain challenges, such as variations in usage; while some are heavily frequented, others are neglected. Even within the same UPS, specific areas may be crowded while other areas remain largely unused or abandoned. The usage of a UPS usually depends on how it is experienced by people, such as whether it is perceived as safe, comfortable, and lively (Weijs-Perrée et al., 2020, Dane et al., 2019, Birenboim, 2018). Failure to anticipate and address these aspects during the design phase of UPSs could lead to dysfunctional urban spaces that cannot meet the needs of the end-users (Rad and Ngah, 2013, Mamaghani et al., 2015, Anderson et al., 2017).

People experience UPSs primarily through their senses, with vision being the predominant sense (Gibson, 1978). Vision allows people to comprehend, evaluate, and interact with their surroundings and facilitates navigation, path selection, and positioning for dynamic and stationary activities within the environment. People’s use of a UPS is heavily influenced by its visibility, which depends on the spatial configuration of the UPS (Gibson, 1978, Hillier, 2004). Therefore, it is important to consider the visibility of an area and its attributes (i.e., trees and buildings) as a design goal.

Visibility assessments (i) to enhance pedestrian navigation from strategic points such as a train station or entry point of UPS towards landmarks (Koltsova et al., 2013) and (ii) to position a landscape attribute (He et al., 2005) have been researched but primarily in design-oriented platforms devised for designers, and often underutilized in engaging end-users of UPSs.

With the advancements in immersive virtual reality (IVR) new methods and tools for participatory urban design that involve potential end-users in the UPS design process, have become possible (Evers et al., 2023, Dane et al., (2024, submitted)). IVR technologies provide an interactive platform for embodied experiences (Klippel et al., 2020), allowing end-users to be involved directly with design processes (Han and Lee, 2022). However, many IVR apps still can not offer real-time feedback (Schrom-Feiertag et al., 2020, Matthys et al., 2023a, Ehab and Heath, 2023) that is particular to spatial arrangement and visibility—which are critical for informed UPS design.

In this study, we will look into CoHeSIVE. CoHeSIVE, an IVR-based co-design application scripted in Unity3D, developed for healthy public space design in previous research by (Evers et al., 2023, Dane et al., (2024, submitted)), enables end-users to automatically generate a new design scenario each time when the end-user selects an alternative level for a particular design attribute (i.e., building height, combination and amount of trees, number of benches, number of light posts). CoHeSIVE demonstrated how IVR tools may support user participation and well-informed urban design decision-making (Evers et al., 2023). However, potential improvements can still be incorporated into the application. In that sense, visibility measures and assessment, such as understanding how much space is enclosed and identifying obstacles that impact the extent and scope of vision, hold particular relevance. These measures serve as important indicators that can assist end-users in comprehending and assessing how their design choices within a given space affect the visibility from various viewpoints.

1.2 Research Aim

This study addresses the gap for the lack of real-time visibility feedback within IVR applications tailored for UPS design and its technical challenge. One of the technical challenges of this gap is that the traditional methods of analyzing visual cognition, such as studying gaze movement patterns, often demand significant time and resources to provide real-time information in IVR applications (Matthys et al., 2023b).

In response, this research investigates the potential of computer vision technology as a feasible alternative for real-time visibility assessment within an IVR application. Therefore, we have developed a new technique that combines Unity3D's integrated callbacks and the ray-casting method to dynamically to track attributes in the user's field of vision. The real-time result of the visibility assessment is presented as a dashboard within the CoHeSIVE app, providing users with quick feedback on how the spatial layout of UPS attributes influences their visibility. This innovative approach lays the groundwork for upcoming developments in IVR-based co-design apps such as CoHeSIVE, which can potentially transform the UPS design process by providing users with real-time visibility insights and enabling better-informed and end-user-centred designs.

2. Materials and Methods

This section firstly explains the CoHeSIVE IVR tool, developed for UPS design. After that, the research approach of this study is elaborated.

2.1 CoHeSIVE IVR App

The project "Codesigning Healthy Public Spaces via Immersive Virtual Environments" (CoHeSIVE), focused on co-designing healthy public space in a participatory way, with people and for people (Evers et al., 2023). The station plaza in the center of Eindhoven, the Netherlands (Figure 1) was taken as a case study. The project introduced a novel methodology for co-designing UPS, specifically addressing the user needs through an IVR application, scripted in Unity3D (Figure 2). One of the key findings of this research project was that IVR applications, thanks to their interactivity and embodied experiences, can serve as a valuable method to incorporate the needs and opinions of end-users and contribute to the decision-making process for a suitable design (Dane et al., (2024, submitted)). However, potential improvements still need further analysis and incorporation into such applications, like real-time feedback on design goals. Real-time feedback on visibility assessment in the CoHeSIVE application can significantly improve design results and user experience. By incorporating these functionalities for real-time visibility assessment, users can dynamically analyze the visibility of different aspects in the virtual environment. This feature enhances the interactive experience and helps to make better-informed and efficient design choices, which advances the general effectiveness of urban public space design.

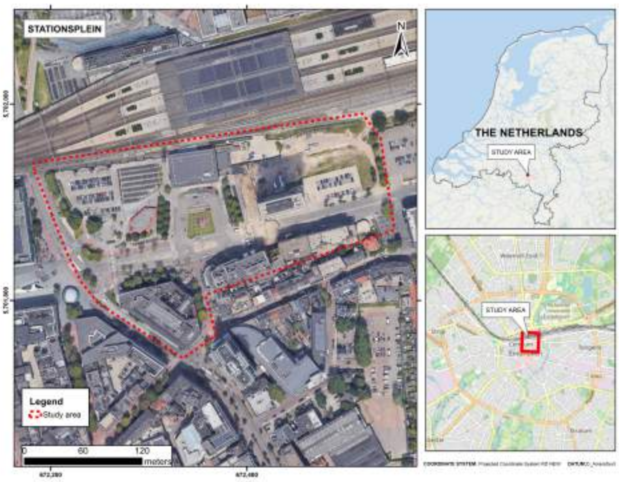

Figure 1. Location of Stationplein, Eindhoven, The Netherlands.

Figure 2. IVR Application developed for designing healthy public spaces .

As described in (Evers et al., 2023, Dane et al., (2024, submitted)), within the application, users are presented with a bird's-eye view of the simulated location. Users can switch between this bird's-eye perspective and three different eye-level viewpoints to experience and interact with the UPS from the egocentric perspective. This is done using the controllers of the VR headset. CoHeSIVE enables users to customize a given base scenario according to their preferences by modifying various design attributes (tree presence, tree composition, benches, grass coverage, height of buildings, lamp posts and water fountain). Within the application, each attribute is displayed sequentially on a selection panel with pop-up buttons, and users can navigate between attributes using the next or previous buttons. Upon clicking a pop-up button for an attribute, users can view, experience, and adjust the levels of that attribute (i.e.; attribute: tree composition and attribute levels: Clustered and Spread).

They can customize the seven available attributes by choosing their preferred levels.

2.2 Research Approach

The research aims to enhance the existing Immersive Virtual Reality Application, CoHeSIVE, by implementing a framework for real-time feedback on the visibility assessment of urban plaza design scenarios.

Established approaches to visibility analysis in urban planning based on Isovists typically involve static simulations or post-processing techniques that do not offer real-time feedback (Turner et al., 2001). Other methods such as studying gaze movement patterns, often demand significant time and resources, making it difficult to provide real-time information in IVR applications (Holmqvist et al., 2011),

In order to address this, our study explores the possibility of assessing visibility in real-time within an IVR application by implementing frustum-based visibility analysis, ray-casting, and Unity’s built-in callback techniques. The camera frustum defines the visible area of the camera, enabling us to dynamically calculate which attributes are within the user’s field of view. The visibility calculations update when a user changes an attribute level in the IVR environment and when the user changes their head position.

The research unfolds in four consecutive phases, delineated as follows (Figure 3):

Phase I - Setting the scene: The research project was contextualized in this initial stage. This step aims to comprehend the current state of the art and identify research gaps. Following this, challenges and strengths associated with existing approaches were identified, along with opportunities for improvement.

Phase II - Framework Development: This phase focuses on developing the main framework of the research. Exploring the relationship between visibility and the user experience of urban public spaces, the study seeks to develop a framework for the existing IVR project CoHeSIVE, particularly for providing real-time feedback on visibility aspects, enabling users to assess the impact of design decisions on the visibility of urban plaza spaces.

Phase III- Implementation: This phase focused on implementing the designed framework into the CoHeSIVE IVR app to enhance its capabilities.

Phase IV - Testing and Validation: This phase is dedicated to testing and validating the designed approach.

The research concludes by discussing the integration of real-time visibility assessment in the IVR app, its implications for urban public space design, and recommendations for future research lines.

3. Results

3.1 Proposed Framework

In this section, we present the results of our framework for real-time visibility assessment in an interactive IVR application for

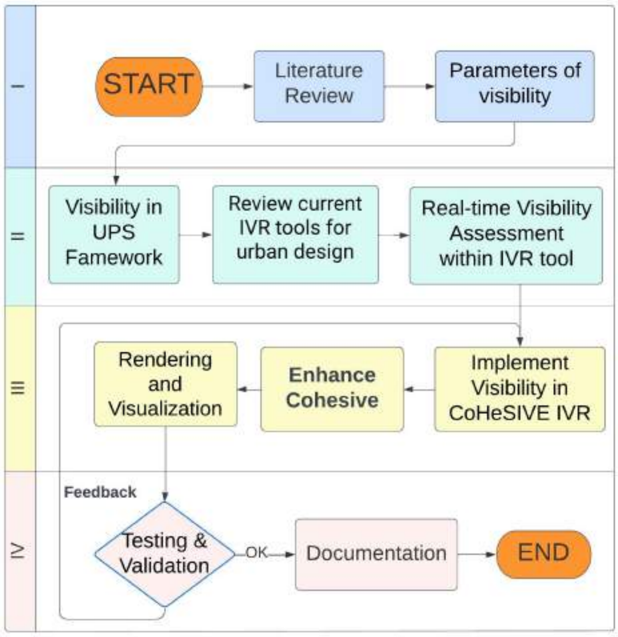

Figure 3. Research approach.

UPS design. Real-time visibility assessment is achieved by implementing the framework in Unity3D and utilizing a combination of Unity’s built-in functions and custom scripts. To implement this framework, we utilized Unity’s frustum to define users’ visibility range (through the camera view) and dynamically calculated the features within the frustum.

3.1.1 Ray-Casting Method:

Our framework uses a ray-casting technique to identify an object’s visibility in the virtual environment. In CoHeSIVE’s simulated environment, an object corresponds to the design attributes, such as trees and buildings. To identify intersections with objects in the field of view of the user, this method entails projecting rays from the camera’s position in multiple directions. By examining the intersections, the user can precisely determine which items are occluded and visible to the viewer.

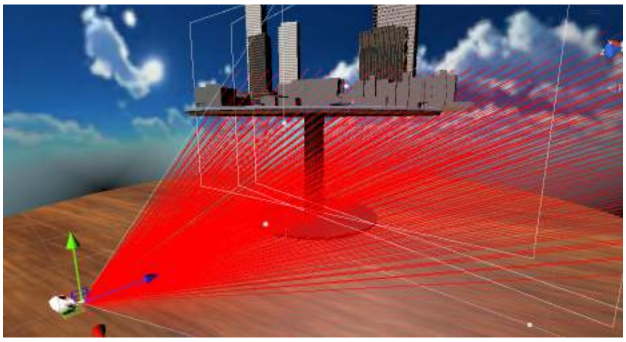

Figure 4. Unity raycasting

Ray-casting is a suitable method for our case study because the IVR scenarios contain only stationary (non-moving) attributes (objects), and therefore, the ray-casting method allows fast processing (Cashion et al., 2012).

Object Visibility is a script for Unity3D that controls an object’s visibility according to whether or not it is in the camera’s field of view. When an object in the scene becomes enabled, it registers it; when it becomes disabled, it eliminates it. It also dynamically tracks changes in visibility status by using Unity's *OnBecameVisible* and *OnBecameInvisible* callbacks.

3.1.2 Unity's built-in callbacks Method: Besides the ray-casting technique implemented (see Figure 4) through the *Object Visibility* script, our system leverages Unity's built-in callbacks to improve visibility assessment. In the context of Unity development, callbacks refer to predefined functions that are automatically called by the Unity engine in response to specific events or conditions during runtime. This is essential because the ray-casting technique alone cannot identify the objects on a large and plane surface such as grass, ground and sky. To determine the visibility of the sky, ground, and grass in the surrounding area, we examine the junctions.

We use the *Unity Physics package*, part of Unity's Data-Oriented Technology Stack (DOTS), which provides a deterministic rigid body dynamics system and spatial query system (Unity3D, 2024, 25 May). Unity Physics offers a robust collision query system that includes ray casting, linear casting, and closest point estimation. These queries allow for efficient collision filtering and user data retrieval. Within the Unity Physics package, we use Raycast scripts to detect if any objects in the user's field of view, such as grass or the ground, are struck by rays cast from the camera (Guo, 2023).

A custom script named *SkyVisibility* was added to this procedure to identify the sky within the view of the field. Additionally, the *custom-created VisibilityHandler* script serves as the main hub for controlling item visibility and adjusting user interface components as necessary. It ensures seamless interaction with the visibility panel by turning input actions on and off using Unity's OnEnable and OnDisable callbacks. It also uses custom events to notify other application components about changes in visibility status.

Figure 5 shows a graphical representation illustrating how the scripts are interconnected and work together to achieve real-time visibility assessment in the Unity3D environment.

3.2 User Interface (UI)

Taking the design of the CoHeSIVE app as a starting point, several improvements were implemented in this study to enhance this app. Figure 5 presents a general overview of the interface of the new enhanced app, which includes a dashboard for real-time visibility assessment.

Starting Menu: A new starting menu (seen in Figure 6) is implemented, allowing the user to modify settings such as daytime (day, night) and weather conditions (rainy, sunny, snowy)(Figure 7). Daytime and weather are implemented to provide external contextual conditions to the users and are not inherent to the area's design.

Opening View: Once the starting settings are chosen, users are shown a bird's-eye view (see Figure 8), which allows them to see a virtual table with the simulated public square displayed on top of it. Then, users can select from the given 3 viewpoints (see orange pins in Figure 8 and 9) provided to teleport to the simulated environment for the egocentric eye-level view (Figure 9).

Attribute Modification: Based on the attributes contained in the original CoHeSIVE app, users can modify the levels of the

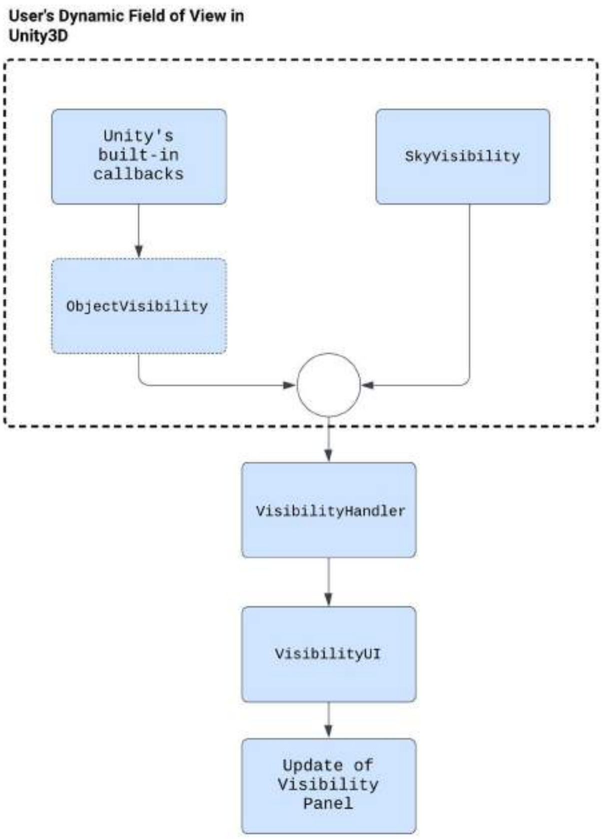

Figure 5. Graphical representation illustrating the interrelation between the four main scripts for this study

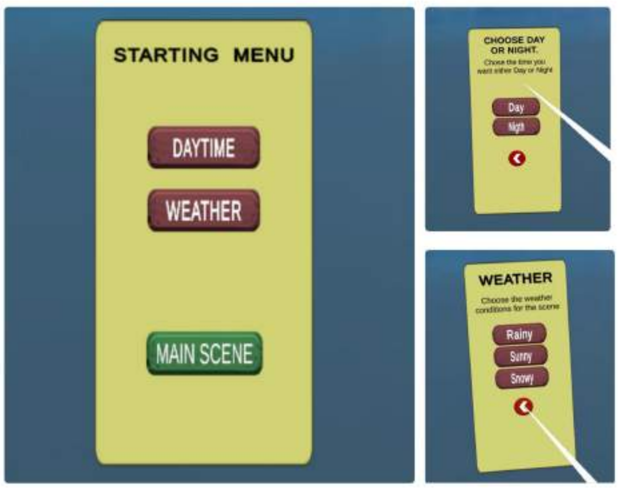

Figure 6. Starting Menu

given seven different design attributes. The attribute levels vary from 3 to 5 (see (Dane et al., (2024, submitted)). Given the number of attributes and their levels, a total of 2048 possible design scenarios can be created by the user. Attribute modification is kept the same as the original(Figure 9).

Real-Time Visibility Assessment: The core of our study involves implementing a dashboard (see Figure 10, 11) to visualize the amount of design attributes within the user's field of view. Based on the type of object (accountable like trees, benches and non-accountable like surfaces such as a

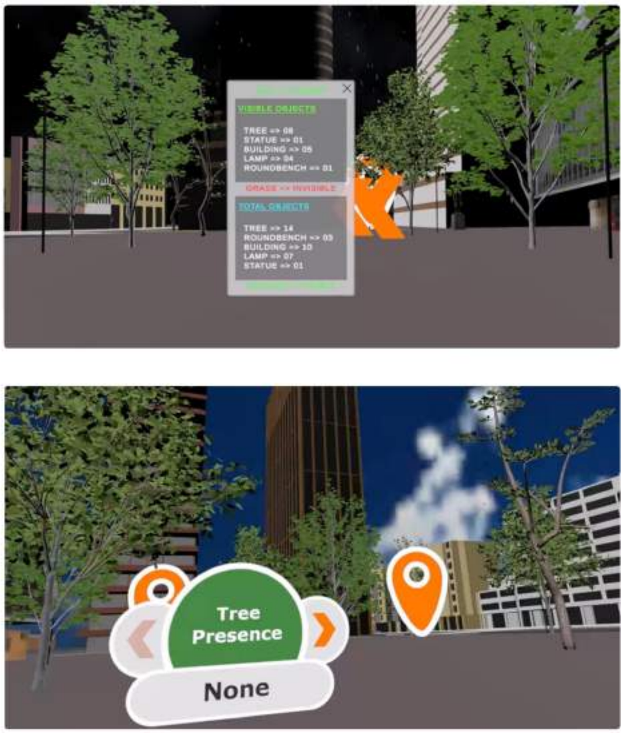

Figure 7. Possibilities of different scenarios

Figure 8. Opening view

grass field), our proposed framework (Ray-Casting Method and Unity's built-in callbacks method) is used to identify the objects present. Our framework utilizes Unity's frustum to define the camera's visibility range, enabling dynamic calculation of the attributes within the frustum (the user's field of view based on the camera). This allows for real-time updates as the camera moves and objects (design attributes) enter or leave its view.

In general, the performance of our approach is strong, with no delays or issues in rendering graphics or graphic motion. The visibility calculation dashboard is dynamically updated in real-time, providing users with instant feedback.

4. Discussion and Conclusions

In this section, we evaluate the results of our study within the context of visibility assessment, contrasting them with the current approaches and suggesting directions for future research and useful applications.

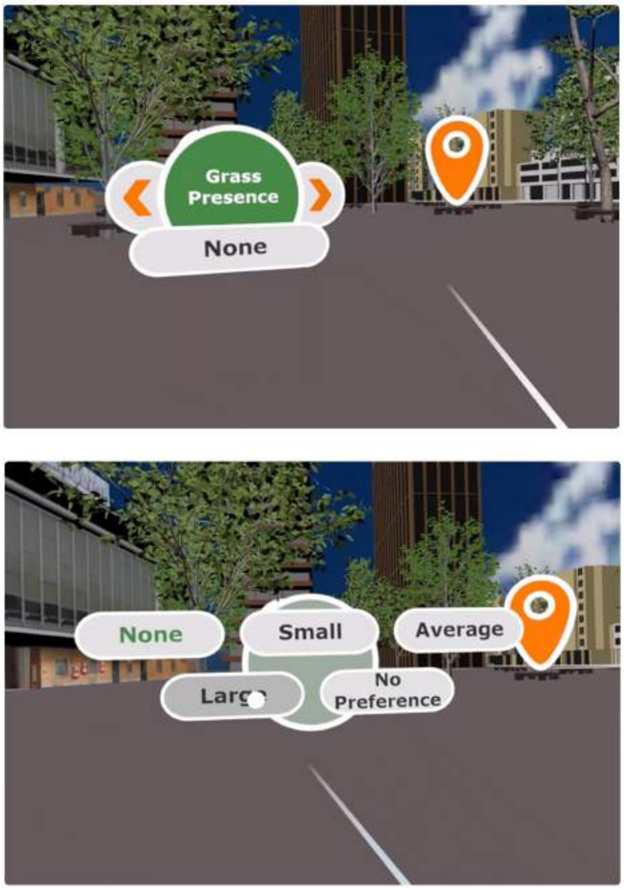

Figure 9. Attribute Modification

In this study, we addressed the gaps: (i) the lack of real-time visibility feedback within IVR applications tailored for UPS design and (ii) its technical challenge: the significant time and resources demanded to provide real-time information in IVR applications. Established methods for visibility analysis in urban planning often rely on static simulations or post-processing techniques, which do not offer real-time feedback and are computationally intensive in VR environments. Such methods typically involve complex algorithms and detailed manual assessments, resulting in delayed insights that can hinder the iterative design process.

Our approach leverages a combination of Unity functions and capabilities, utilizing the Unity frustum to define the camera's visibility range. We dynamically calculate the attributes visible in the user's field of view based on what is within that frustum. This enables real-time updates as the camera moves and attributes enter or leave its view. By implementing frustum-based visibility analysis, ray-casting, and Unity's built-in callback techniques, we provide an efficient and responsive solution for real-time visibility assessment.

As added value of our research, our approach delivers immediate feedback, unlike traditional methods that provide delayed visibility assessments. This is crucial for iterative design processes, enabling designers and end-users to make prompt and informed decisions. Our system updates visibility calculations dynamically based on user interactions and movements

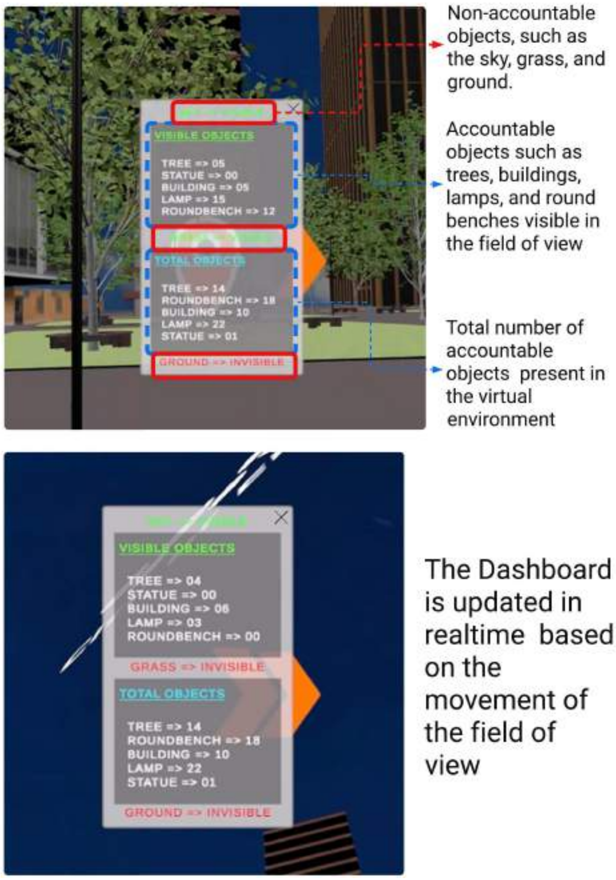

Figure 10. Dashboard for Real-time Feedback Visibility Assessment

Figure 11. Dynamic Visibility Assessment

within the IVR environment. This contrasts with static simulations, which cannot adapt to changes in real-time to provide a more immersive and interactive design tool. Additionally, our method accurately identifies visible objects, including those on large, flat surfaces such as grass and ground. This comprehensive approach enhances the reliability of visibility assessments compared to traditional static methods.

As future improvements and directions, we propose the following points.

- Non-Stationary elements: The visibility assessment performs well in the current implementation, as the virtual environment consists solely of stationary elements. However, for future improvements of the app, we propose the inclusion of non-stationary objects and adapting the approach to accommodate dynamic conditions.

- Dynamic Lighting: We added daytime and weather conditions as external circumstances for this app. These conditions can affect the visibility of the users due to shadows and reflections. However, they are currently not considered for the visibility assessment within the app. Integrating dynamic lighting calculations into the framework can provide more accurate visibility assessments, taking into account factors such as shadows and reflections.

- Visibility Assessment: The visibility assessment reports the amount of attributes within the user's field of view. Although this is useful to the end-users in the co-design process, they might need more information regarding visibility, such as the share of attributes within the whole view field. Moreover, a future study could incorporate the horizon's visibility from one viewpoint to another. This would help understand which areas could be blind spots and, therefore, less frequented in a UPS.

- User Interface Enhancements: The user interface functions, such as the starting menu and the visibility assessment dashboard, are added to the app. They are (de)activated via the controller buttons of the VR headsets. This might result in usage difficulties for some users. Moreover, the visibility assessment dashboard is heavily based on text information that might not be easily interpreted by the users. Therefore, the dashboard can make use of simple visualizations such as graphs. The user interface enhancements should be evaluated by users in a workshop setting in terms of ease and intuitiveness.

- Understanding the user's central visual field attention: The central visual field is often defined as the region within the field of view where visual attention is high. Building upon this concept, the Gaussian distribution model provides a framework for understanding the distribution of visual attention across the field of view. According to this model, attention is concentrated at the center of the field of view, gradually diminishing towards the periphery in a symmetrical bell-shaped curve. Our research doesn't incorporate this principle; future research could benefit by exploring and implementing such a concept.

- New Approach Based on Ray-Casting Method Only: Our research defines the use of the ray-casting approach to assess visibility within IVR environments. Future research could follow this direction to develop a ray-casting only approach for assessing the visibility percentage of different features of interest within our field of view, such as the percentage of greenery, built-up area, water, etc.

Such IVR co-design tools help end-users experience and interact with potential future design scenarios of a UPS. Adding assessment dashboards, like the visibility assessment in this study, enables users to make more informed design decisions. By incorporating the suggested improvements and exploring future directions, our framework can continue to support participatory urban design, empowering end-users and designers of UPSs to create more visually appealing and functional public spaces.

References

Anderson, J., Ruggeri, K., Steemers, K., Huppert, F., 2017. Lively social space, well-being activity, and urban design: findings from a low-cost community-led public space intervention. *Environment and Behavior*, 49(6), 685–716.

Birenboim, A., 2018. The influence of urban environments on our subjective momentary experiences. *Environment and Planning B: Urban Analytics and City Science*, 45(5), 915–932.

Cashion, J., Wingrave, C., LaViola Jr, J. J., 2012. Dense and dynamic 3d selection for game-based virtual environments. *IEEE transactions on visualization and computer graphics*, 18(4), 634–642.

Dane, G., Borgers, A., Feng, T., 2019. Subjective immediate experiences during large-scale cultural events in cities: A geotagging experiment. *Sustainability*, 11(20), 5698.

Dane, G., Evers, S., van den Berg, P., Klippel, A., Verduijn, T., Wallgrün, J. O., Arentze, T., (2024, submitted). Experiencing the Future: Evaluating a New Framework for the Participatory Co-design of Healthy Public Spaces Using Immersive Virtual Reality.

Ehab, A., Heath, T., 2023. Exploring Immersive Co-Design: Comparing Human Interaction in Real and Virtual Elevated Urban Spaces in London. *Sustainability*, 15(12). https://www.mdpi.com/2071-1050/15/12/9184.

Evers, S., Dane, G. Z., van den Berg, P. E., Klippel, A. K., Verduijn, T., Arentze, T. A., 2023. Designing healthy public spaces: A participatory approach through immersive virtual reality. *AGILE: GIScience Series*, 4, 24.

Gibson, J. J., 1978. The ecological approach to the visual perception of pictures. *Leonardo*, 11(3), 227–235.

Guo, C., 2023. Evaluation of Acceleration Structures for Ray Casting in Physics Scenes.

Han, J., Lee, S., 2022. RESIDENT'S Satisfaction in Street Landscape Using the Immersive Virtual Environment-Based Eye-Tracking Technique and Deep Learning Model. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 45–52.

He, J., Tsou, J., Xue, Y., Chow, B., 2005. A Visual Landscape Assessment Approach for High-density Urban Development. *Proceedings of the 11th International CAAD Futures Conference*, Austria, 125–134.

Hillier, B., 2004. What it Looks from Here: questions and conjectures about spatial cognition from a ‘syntactic’point of view” workshop 8. *Mental Conceptions of Emergent spaces in Architectural Design, Design computing cognition*, 4, 9–20.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., Van de Weijer, J., 2011. *Eye tracking: A comprehensive guide to methods and measures*. oup Oxford.

Jalaladdini, S., Oktay, D., 2012. Urban public spaces and vitality: a socio-spatial analysis in the streets of Cypriot towns. *Procedia-Social and Behavioral Sciences*, 35, 664–674.

Klippel, A., Zhao, J., Oprean, D., Wallgrün, J. O., Stubbs, C., La Femina, P., Jackson, K. L., 2020. The value of being there: toward a science of immersive virtual field trips. *Virtual Reality*, 24,, 753–770.

Koltsova, A., Tunçer, B., Schmitt, G., 2013. Visibility analysis for 3D urban environments. *Proceedings of the 31st International Conference on Education and research in Computer Aided Architectural Design in Europe*, Delft, The Netherlands, 375–384.

Mamaghani, N. K., Asadollahi, A. P., Mortezaei, S.-R., 2015. Designing for improving social relationship with interaction design approach. *Procedia-Social and Behavioral Sciences*, 201, 377–385.

Matthys, M., De Cock, L., Mertens, L., Boussauw, K., De Maeyer, P., Van de Weghe, N., 2023a. Rethinking the Public Space Design Process Using Extended Reality as a Game Changer for 3D Co-Design. *Applied Sciences*, 13(14). https://www.mdpi.com/2076-3417/13/14/8392.

Matthys, M., De Cock, L., Mertens, L., Boussauw, K., De Maeyer, P., Van de Weghe, N., 2023b. Rethinking the Public Space Design Process Using Extended Reality as a Game Changer for 3D Co-Design. *Applied Sciences*, 13(14), 8392.

Mehta, V., 2014. Evaluating public space. *Journal of Urban design*, 19(1), 53–88.

Rad, V. B., Ngah, I., 2013. The role of public spaces in promoting social interactions. *International Journal of Current Engineering and Technology*, 3(1), 184–188.

Schrom-Feiertag, H., Stubenschrott, M., Regal, G., Matyus, T., Seer, S., 2020. An interactive and responsive virtual reality environment for participatory urban planning. *Proceedings of the 11th Annual Symposium on Simulation for Architecture and Urban Design*, 1–7.

Turner, A., Doxa, M., O'sullivan, D., Penn, A., 2001. From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and Planning B: Planning and design*, 28(1), 103–121.

Unity3D, 2024, 25 May. Unity Physics package. *Retrieved from: https://docs.unity3d.com/Packages/com.unity.physics@1.2/manual/index.html*.

Weijs-Perrée, M., Dane, G., van den Berg, P., 2020. Analyzing the relationships between citizens' emotions and their momentary satisfaction in urban public spaces. *Sustainability*, 12(19), 7921.