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Visualizing Invisible Environmental Data in VR: Development and Implementation of Design Concepts for Communicating Urban Air Quality in a Virtual City Model

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Abstract. As cities continue to grow, the desire to combine densification with sustainability and greenery may present a challenge to air quality, resulting from reduced ventilation caused by dense buildings and vegetation. To support the careful urban planning required, effective and interactive tools that can visualize and communicate information about air quality to stakeholders are essential. In a transdisciplinary research project aiming to explore such visualizations a prototype pedagogical virtual reality tool was developed, allowing users to explore the impact of aspects of the built environment upon urban air quality. The tool was evaluated with adolescents in upper secondary school through interviews and observations, as well as with the general public through a questionnaire study. This paper provides insights, potential solutions, and initial assessments relevant to data visualization in 3D and immersive analytics in urban planning and stakeholder communication. Identified challenges include difficulties with color association and data distinguishability, and as well as tool complexity relating to the many features requested by experts involved in a transdisciplinary project.

Keywords: Data visualization · Urban planning · Air pollution data · 3D-city model · Virtual reality · Usability study

1 Introduction

An important goal for future cities is to create sustainable, green, and dense urban environments [1]. For this end it is crucial to understand how vegetation, building structures and traffic affect air quality. Digital tools with a high degree of interactivity can promote dialogue with groups not usually involved in urban transformation processes [2] and enhance citizen involvement, thus bridging the gap between planners and citizens [3,

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4]. In this context 3D-city models can provide a better understanding of increasingly vertical cities [5]. Easily comprehensible visualizations that can be explored intuitively and draw public attention, promote engagement, and spread awareness about air pollution [6]. Immersive Virtual Reality (VR) enables embodied interaction, enhances the user experience, and facilitates understanding by relating new information to relevant contexts [7]. However, the range of possible interactions in immersive VR presents a challenge, in particular when combined with visualizations of realistic 3D-environments and associated variations in available views [8]. Interactive visualizations also need to be adapted to the needs of laymen [9]. Given the richness of a medium aiming to imitate reality, the discussion of additional design concepts for presenting data in specific scenarios is a valuable contribution to mapping out the full scope of the field.

The research presented in this paper was carried out within a transdisciplinary, three year-long research project[1]. The project was a collaboration between research and development competences involving environmental sciences, urban planning, interaction design and visualization. The goal of the project was to create a prototype of a virtual tool for identification, visualization, and communication of air quality where users can explore how vegetation, building formations, street widths, traffic and wind directions impact urban air quality across different scenarios.

This paper focuses on learnings from the design and development of complex data visualization in a transdisciplinary project and reports from field tests with intended end users. This includes user feedback on implemented interaction methods and visualization techniques that may inform future work. Here, we present initial results connected to the focus for this paper. Additional analysis is currently ongoing.

2 Background

A central challenge for implementing visualization as a communication tool in urban planning is visual representation [10]. To facilitate communication with the public, information must be presented in an engaging easy-to-understand manner [11, 12]. Traditionally, 2D-maps are used to analyze and communicate environmental impacts from e.g., noise or air pollution. However, for non-experts it can be difficult to connect numbers or abstract color scales in a 2D-map to a real-life scenario [13, 14]. Linked to this is the difficulty of showing different types of data together in 2D-maps to clarify correlation effects between different parameters. With increased densification cities are becoming more vertical, further limiting the use of 2D for conveying detailed information about the situation in a specific area [15].

In urban planning processes 3D-city models are increasingly used for analysis, decision making and communication. Displaying information in 3D allows for a heightened recognition factor – as maps are an abstraction of reality, a 3D-model enables an increased degree of realism [9, 16]. When visualizing abstract invisible parameters, the flexibility of 3D-media is advantageous, since a visualization grounded in reality can be augmented, for example, to display parameters that are invisible to the naked eye. Exploring these 3D-visualizations in immersive VR allows users to be able to interact

[1] https://www.mistraurbanfutures.org/sv/projekt/cityairsim-ska-visa-hur-trafik-gronska-och-tatt-byggande-paverkar-stadsluften.

with the model and strengthen the user experience [17]. VR interaction with a 3D-model allows the user to move around and look at a city street or proposed construction from different perspectives [9]. To easily be able to explore presented data in a naturalistic virtual environment can facilitate the understanding of what a scenario would entail in real-life [18]. A user can thereby be aided in connecting the information to a realistic situation, which can make for a memorable experience and have an impact on future actions and decisions [19]. However, it is important to point out that different techniques and tools are better suited for different aspects of communication and target groups [20, 21].

The need for a multidisciplinary approach in the development of real-time 3D-simulation tools is highlighted by Christmann [22], who emphasizes the importance of the human factor and to make data intelligible to both experts and non-experts. There has been an increase in usability studies focusing on the use of 3D-visualizations and VR within urban planning in recent years [14, 20, 22–24]. A variety of projects have been conducted using 3D-visualization to communicate air quality data, aiming to display data for analysis, and raise awareness among the public [25–27]. Teles et al. [25] developed a tool with air quality sensing data using a game-like 3D-environment. Using gamification, their aim was to engage non-experts and increase awareness of air quality. Isikdag and Sahin [26] developed a web based interactive system for visualizing air pollutant levels, focusing on high-volume geospatial data. They acknowledged the importance of visualizing information connected to city objects in different LODs. Ujang et al. [27] studied the use of a spatial 3D-city model for air quality monitoring. They concluded that visualization in 3D will improve the visual analysis for understanding the behavior of air pollutant dispersion. However, improvements could be furthered through identifications and analysis of different layers of air pollution concentrations with a topological data structure in 3D [27].

By visualizing air pollution data in a 3D-city model, an improved understanding of environmental impacts can be conveyed [28]. However, the combination of visualizations of invisible pollution data with a realistic background presents challenges that make it crucial to consider how factors of the visual expression can provide a clear contrast between the visualized data and the background in order to minimize the risk of misinterpretation to convey the information correctly and [8, 29–31]. Such factors include for example choice of shape of the visualized data, such as surfaces, lines, points, volumes, 3D-grids or heatmaps. For the information to be clarified and identified in relation to its context it is often necessary to define different visual properties for each geometric shape, such as textures, patterns, and color [32].

Traditionally, color plays an important role in cartographic visualization [33, 34]. Depending on the target audience, cultural or natural associations are important to consider [35], including divergent color vision. Today, the rainbow scale is widely used for visualizing air quality data [33–35], however this scale is also criticized for being difficult to perceptually interpret [34]. Gautier and Brédif [36] suggest that an interactive 3D-visualization of data therefore should provide the possibility to dynamically change between a rainbow color scale and alternative color scales, based on a range in luminance. Other suggestions include the use of a single-color ranging from low to high intensity, or to use other attributes, such as shapes [35].

The perception of color in a model is also linked to the perspective the visualization will be viewed in. Most 3D-city models today use birds-eye view rather than street-level view. The street-level view is however important for evaluating how complex urban changes affect life in the city [37]. Movement through the model in a street-level view perspective combined with an overall view can furthermore facilitate understanding about how e.g., a new building will affect the surroundings [37, 38].

3 Methods and Development Process

The project was conceived as an iterative, user-centered design [39], mixing methods for evaluation. The application was designed as a communication tool for understanding the impact of greenery in urban landscapes, primarily regarding air quality. Workshops with educators and urban planners were arranged to discuss needs and ideas for implementation. Early prototyping was used together with sketching to communicate complex development tasks involving data visualization, scenario design and VR interaction design. Evaluations of the material were made both in the smaller work package group as well as discussed with researchers, developers, and project partners. Throughout the development the prototype was shown to representatives of target groups. Feedback from these sessions formed a base for refinements. The visual concepts developed here also represent a continuation of previous work by the project participants [30, 31, 40] on developing methods for the visualization of invisible environmental data in 3D.

Methods were developed for visualizing simulated research results, based on an inventory of needs through discussions with representatives of the target groups. The design work focused on two areas: 1) modelling of data (nitrogen dioxide (NO_2) and particulate matter (PM_{10})), where a city model was developed with different scenarios for, e.g., buildings and street width; and 2) representation of data, where concepts for air quality were visualized. The visualizations were combined with the city model in an interactive VR-environment, facilitating interactive and contextual exploration. User tests to evaluate results were part of the refinement process to validate updates and different versions of the application. Due to the Covid-19 pandemic all user testing during the development in 2020 and 2021 was done remotely, using Zoom.

3.1 Modelling of Scenarios and Data

As a case area a district in central Gothenburg was chosen as it currently is considered for future replanning and because it is affected by heavy pollution from the nearby motorway. A baseline model, corresponding to the current status of the case area, was developed in Autodesk 3Ds Max, as well as additional building scenarios along the street (see Fig. 1A–C). These models were combined with surrounding environments, greenery, lighting, and additional environmental features, in Unreal Engine (version 4.26) to produce interactive 3D-environments corresponding to different scenarios. Interaction enabling real-time exploration in VR was also developed in Unreal Engine, as well as concepts for visualization of air pollutants.

The scenarios were designed for the user to explore the impact of different building and vegetation configurations affecting the air quality through air flow and circulation.

Fig. 1. **A–C.** Screenshots of scenarios from the application, **A)** today's 3-storey buildings, narrow streets, no vegetation, easterly wind, NO_2, a) The focused-on street, and b) the adjacent E20/E6 motorway, **B)** wide street without trees, **C)** wide street with row of deciduous trees.

Four fictitious building scenarios were designed, for 5 building variations, and combined with a narrow or wider street to create scenarios covering a diverse set of different preconditions. The different building scenarios included buildings of different heights as well as a potential blocking "barrier building" facing the motorway. Additionally, scenarios with different kinds of vegetation were developed including green walls and different placements of deciduous trees (see Fig. 2).

The visualized data was based on computer simulations and covered a volume of $512 \times 512 \times 64$ m, with one data point for each cubic meter, provided as NetCDF from project participants responsible for the data simulation. In a pre-processing step, this NetCDF data was converted to images that can be read into Unreal Engine as data textures and used in shader-based materials and particle systems (Niagara) for fast real-time visualization of the data. The application was tested and designed mainly with Meta Quest 2, connected to a desktop computer, in mind.

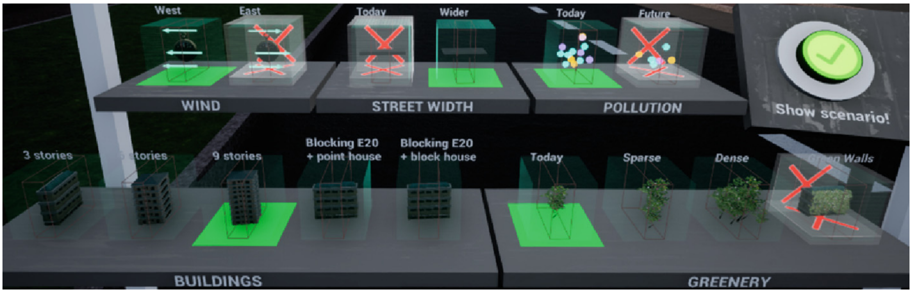

Fig. 2. Boxes that combine to select scenarios. Green is selected. Crosses indicate that boxes cannot be combined, as not all scenarios were included in the prototype (Color figure online).

3.2 Visual Exploration of Data: Visual Design and Concepts for Air Pollution

Concepts were developed for how shape, color and background conditions can be used in a virtual 3D-model for displaying NO_2 and PM_{10}. Various visual concepts for the visualization of the pollution data were developed and tested. Eventually three concepts were chosen: 1) volumetric particles, 2) large cut planes, and 3) small cut planes. Firstly, particles were spawned in the entire data-volume, colored by, and moving according to the data. Thresholds were used to hide particles outside of a certain range, e.g., to reduce clutter (see Fig. 3A). Secondly, a pair of large cut planes with a heatmap of the pollution levels, one horizontal and one vertical, were implemented to cover the entire data volume in their respective planes. These cut planes could be shown or hidden, with the possibility to move them up/down or back/forward (see Fig. 3B). Thirdly, small cut planes were designed to facilitate examination of data by pointing the hand controller in a direction and firing a cut plane. The cut planes also included a text with the current data value at the center of the cut plane. The cut planes could be held in place by holding down the trigger button on the VR-controller to exactly sample nearby data values (see Fig. 3C).

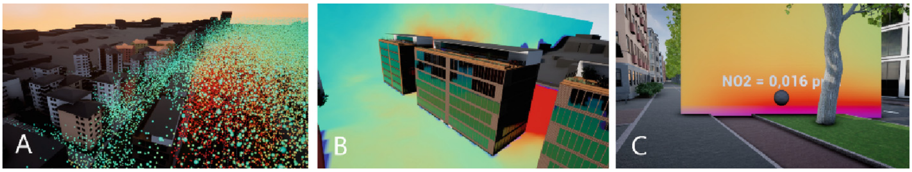

Fig. 3. **A–C. A)** Volumetric particles, **B)** a movable large cut plane with a heatmap, and **C)** small cut planes to be fired from the user's hand.

The particle visualization was intended to give a quick overview of the pollution levels, while the cut planes were designed to facilitate a closer and more deliberate exploration. Several attributes concerning shape were investigated such as density and scale of the particles. However, we noted that the nature of a particle system in a realistic 3D-environment made it difficult to distinguish if changes in saliency were caused by color, size, or density. Thus, we chose in the end to only encode the scalar data into color. Tests to enhance visibility of particles were done throughout the development of the prototype, e.g., using different color scales, and encircling particles with a black outline [29].

10 different color scales were developed based on different principles, e.g., light to dark, or transparent to opaque. These were then tested in the model. Some scales were based on scales we developed in previous research projects. Others were, or were adapted from, already existing color scales. They covered different parts of the color circle and included different number of steps to facilitate investigation of how many steps visually worked in the visualization of particularly particles. The criteria for the choice of scales were that they should work in 3D and be easily distinguishable from the environment. Eventually four scales were chosen (see Table 1). Three of these scales (A, B, C) were designed for the most common color deficiencies.

To facilitate presence and enhanced understanding for the visualized data different perspectives were intended to be used in the model. To get a more general understanding of the air pollution data through an overview of the model the user could enter a birds-eye view; to facilitate experience of the model in more detail, and at human scale, a street-level view was included. Users could move freely between the different perspectives, choosing which to use.

Table 1. The four final scales implemented in the prototype version of the application.

	Scale	Reference
A	Diverging lightness scale ranging from blue to red 	Adapted from ColorBrewer https://colorbrewer2.org/
B	Sequential scale from light to dark on the yellow-red part of the colour spectrum 	Adapted from ColorBrewer https://colorbrewer2.org/
C	Diverging scale from blue to light yellow, adapted for common colour deficiencies 	Adapted from Ware (2004)
D	Rainbow scale (Jet) 	Scale from Matplotlib https://matplotlib.org/stable/tutorials/colors/colormaps.html

In addition, an investigation was done where specifically the distinguishability of visualized data against a detailed background was studied [29]. Through a Likert scale [41] 87 respondents evaluated the visibility and balance between the 3D-background and data visualization of particles. Screenshots were used with two background lightning conditions (light and dark), two separate color scales (see Table 1, scale B and D) as well as two camera perspectives (birds-eye view and street-level view) [29].

3.3 User Studies

Evaluations of the prototype were conducted during the whole development process, in which the visual visualization of data was one examined aspect. The evaluations were made as weekly reflections within the visualization team, reflections outside the team, in focus group discussions and workshops, lab tests, field tests and in a questionnaire study investigating the impact of background conditions on distinguishability (see Fig. 4).

- **Reflections within the visualization team.** In weekly meetings the team (researchers and developers) reflected together, as well as tested ideas in Unreal Engine. If a specific issue demanded more time, additional meetings or internal workshops were conducted to find a solution.
- **Reflections outside the visualization team.** Meetings with the expanded project network (the different partner organizations, comprising expertise's in science communication, environmental sciences, 3D-visualization, architecture, interaction design)

were conducted throughout the project with e.g., idea generation regarding different aspects of the development process, and problem solving of identified issues in the development.

- **External focus group discussions.** Meetings with stakeholder representatives (e.g., teachers and urban planners) were conducted throughout the project with needs inventory discussions and idea generation regarding various aspects of development. The groups varied in number of participants, from 3–16, and in areas of expertise according to development needs.
- **Questionnaire study.** A questionnaire study about distinguishability of data in virtual environments was conducted between March and June of 2021 with 87 participants from the public, through a master thesis affiliated with the project [29].
- **Lab tests.** Prototype testing was conducted through lab tests in June 2021 where 9 individual user tests were done remotely to identify and resolve errors in the prototype. Interviews were conducted with each user.
- **Field tests.** Field tests were conducted between November 2021 and March 2022 with approximately 190 students, aged 15–18, from 4 schools, as ethnographic studies to observe authentic learning activities with the prototype. Participants were informed about pollution before the sessions and had discussions afterwards. Observation notes were taken during the VR sessions, where participants were in groups of approximately 4. After each session, they were interviewed in groups ranging from 5–15 participants. Both discussions and interviews were recorded and later transcribed.
- **Analysis of results.** The data transcribed from the 15 group interviews and 14 discussion sessions constituted approximately 14 h of recorded material. An in-depth analysis of the transcribed material is currently ongoing. For this paper's purpose, an initial analysis was conducted using a Miro-board to categorize and identify qualitative material relevant to the present topics.

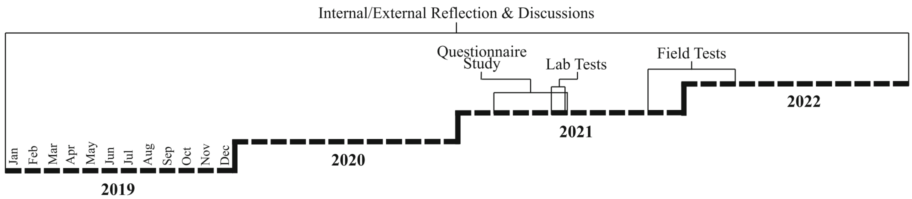

Fig. 4. Graph of user studies timeline from 2019 to 2022, describing data collection. This paper presents initial results. Additional analysis is currently ongoing.

4 Results

The result section is primarily based on qualitative user feedback and observations from the field tests with students connected to the focus for this paper. Results from the questionnaire study on distinguishability are presented briefly as well.

4.1 Interaction and Behavior

Based on observations of the interaction with the visualization tools during the field tests (volumetric particles, small cut planes, large cut planes), almost none of the participants used or showed an interest in using the large cut planes. This is reflected in comments made during the interviews, e.g., *"The wall [large cut plane] […] wasn't really that useful […]"* and *"It wasn´t that clear on what we had to do to get it [the large cut planes] to work."*

Regarding color scales, few participants were observed to change from the default rainbow color scale of the application for the visualized data. This was noted in the interviews as well where participants, when asked if they tested the different color scales, typically answered with a simple "no."

Both perspectives (street-level and birds-eye view) were used by the participants. The function to switch between them was commonly used, with a few exceptions preferring to stay in one perspective. During the interviews and discussions, the participants elaborated on this behavior stating that, e.g., "*[The volumetric data] was helpful in birds-eye view […] to see where the most […] amount of pollution was, to get an overview […] so that I could go down there [to street-level view] and explore more deeply."*

4.2 Understanding and Preferences

While there were both positive and negative comments relating to understanding of the visualization in VR the majority were positive about the overall experience and reported enjoying using it. Positive comments include that the application was "fun", "engaging" and "a novel approach to learning". Many of the given comments could be reflected in e.g.: *"You got a better idea than if you just […] listened", and "If it was just a type of computer program that you sit in front of […], it wouldn't have been as interesting".* Negative comments can be exemplified with remarks like "*It was fun playing in there, but I didn't learn anything".* Other critical comments concerned difficulties understanding what the visualized data meant, and the complexity of VR as a medium. Some thought that VR helped their learning, and gave comments such as *"For me, who hadn't tested much in VR before, it was a fun way to learn new things. I probably would have learned less if I had done it in a different way,"* whilst others did not agree, e.g. *"I had probably learned more […] with lessons […] because I found it too complicated."*

Several comments regarding the visual design and the visualization concepts with particles, large cut planes, and small cut planes were also identified. Positive comments included that *"It [the particles] is good for showing [data] quickly and clearly."* The particles were not however considered to provide more in-depth information, exemplified with: "*[…] it is clear what [the particles] visualized, but what you only understood was that 'here is a little less' and 'here is a little more', no more than that".* The functionality of the large cut plane was considered difficult to understand by many. Almost no one indicated a preference for the large planes. The smaller cut planes were generally considered easier to use and provided better understanding of the data because of the written values, e.g. "*I find the numbers [on the small cut planes] clearer, because with just colors it becomes a bit unclear."* Participants also liked how the colors changed as the cut planes moved through the data when fired, as they clarified the pollution levels throughout the environment. Furthermore, feedback indicated that using the small cut planes had a positive effect on their enjoyment and engagement, e.g. *"I think it [small cut planes] was the most fun! To be able to see how it [concentration of pollution] changes [...]. I liked the colors [...] and to see them change, and to be able to see how it [the numbers and colors] changed from one ppm [...] to another ppm, and then understanding that for example up there [above the buildings] there was less [concentrated pollution], and that is better [air quality]."*

Participants who used the default color scale (rainbow) commented that it was easy to understand, and that red meant high values and green and blue meant low values, e.g. *"I liked the colors [of the rainbow color scale]. [...] Blue is better [air quality] and [...] when it comes to red it is less good [air quality]"* and *"We [as people] think that greenish colors are better than red ones. That is the perception I have."* Many participants, however, commented that it was difficult to interpret the meaning of the colors alone, and that they would have liked them to be linked to a practical meaning and the impact on humans, e.g. *"What does the numbers and colors actually mean? What practical implications does it have on the human body?"* Another participant reported having a color deficiency and was unable to distinguish any data based on color.

During the interviews there were some statements regarding distinguishability, e.g., *"[...] when you were in [birds-eye view] it [the particles] was helpful. But, when you were on the ground [street-level view], it was quite difficult to distinguish."* These comments are in line with results from the investigation on distinguishability [29] where particles were noted by respondents as harder to distinguish in the street-level view compared to the birds-eye view. Neither of the two color scales (see Table 1, scale B and D) that were used was shown to be significantly more effective against the 3D-background ($p = 0{,}677$). However, both perspective ($p = 0{,}002$) and background light condition ($p < 0{,}001$) had a pronounced impact in this regard. Participants reported the particles as harder to see with a light background regardless of perspective, but on the other hand, in the dark conditions they reported difficulty seeing the urban environment instead [29].

5 Discussion

5.1 Visual Exploration of Data

While related research areas such as 3D-visualization and immersive analytics are advancing rapidly [8], many aspects of the conditions for such visualizations are changing quickly, e.g., with developing capabilities and applicability of technology, and much remains to be investigated. This paper informs continued research by presenting learnings, with potential solutions and initial assessments, connected to complex usage scenarios, specifically related to urban planning and communication with stakeholders. Further research, building on these starting points, is needed to draw more generalized conclusions.

Among participants, there was satisfaction with the solution using volumetric particles and the small cut planes. One reason for the preference towards the volumetric visualization could be that, as suggested by Gautier and Brédif [36], it provides a quick overview of the entire distribution of data in the model. The volumetric particles were visible as default and the small cut planes were created and manipulated easily, with one button press and direct hand movements. In contrast, few students used the large cut planes. This may be related to the more complicated interaction required for this feature; based on a menu that many participants missed, or because the users did not see the need for it, as they were satisfied with the combination of particles and small cut planes.

Color plays a key role in communicating information. Miscommunication can arise if a color scale is not used thoughtfully, as demonstrated in a study by Weninger [42], where noise pollution levels proved to be assessed higher if brighter colors were used. While most participants in our study were able to use the default rainbow scale to correctly associate which colors represented high and low pollution, it was repeatedly remarked that it was hard to associate colors to a specific pollution level and actual impact. One approach to address this, which was discussed during the project, was to use color scales based on limit values, such as air quality guidelines (AQG), relating to health impacts of air pollutants [43]. AQG are statistical constructs to protect the population from harmful air pollution levels. In reality, health effects do not suddenly appear at a certain pollution concentration. Rather, the health risk increases with exposure level in a way that can be complex. Consequently, it may be challenging to associate environmental risk with colors in a simple way.

When it comes to distinguishability, we did a lot of testing and self-evaluations to create better visual salience, such as giving the particles dark outlines. This improved visibility regardless of perspective, with the dark outline contrasting against bright backdrops and the lighter center against dark backdrops [29]. Another challenge was with how visual representations in a space occlude the space and data behind them [22, 32]. In our case, getting an overview of the particles was facilitated by wind simulation movement, ensuring that these did not obscure the same background space across time. This also avoided potential misinterpretation of random movement [22, 36], which was discussed as an option. To solve this problem, Christman et al. [22] suggests that a user could be given the option to restrict the area showing the air flow.

Concerning the two perspectives, the benefit of including both street-level view and birds-eye view was supported both by observed use and statements in interviews. It showed appreciation for having both options to use according to their preference and needs, and not only provide the traditional birds-eye view, as often in previous research [37, 38]. However, more data is needed to make reliable conclusions.

5.2 The Development and Result of the Prototype

We could see in the user tests that many participants liked to interact with the application and thought it was fun and looked nice. However, visual aesthetics is different from providing optimal understanding, and we realized that herein lays a conflict. While they liked the experience and aesthetics, they did not necessarily completely understand the content of it. Therefore, more work and further study is needed regarding e.g., guidance and selection of viewpoints.

The project had high ambitions regarding prototype and design development, where the aim was to incorporate many features and as many of the intended scenarios as possible. Many features were developed and implemented, but in the end, many features were not used by the participants. This, e.g., included a possibility to adjust color scale spans which few users explored. Perhaps an alternative development method could have been to work with a so-called vertical slice [44], an in-depth section of the application with only a selected few scenarios in focus.

User study comments and observations indicated that the resulting application was perhaps more suited for expert-users than for non-experts. The complexity of the application was a possible result of continuous influence from experts within the project team and from representatives of end-users involved throughout development. Earlier user testing and systematic communication with the actual end-users could have aided in balancing the complexity. This was however difficult to achieve due to the restrictions and safety precautions during the COVID-19 pandemic.

6 Conclusion

This paper explores complex air data visualization using interactive 3D and immersive VR in a transdisciplinary project on urban planning and stakeholder communication. Field test observations and interviews with students who used the implemented interaction methods and visualization techniques are presented, as well as a questionnaire study on distinguishability. One finding was the preference for a combination of volumetric particles and small cut planes over traditional large cut planes. Results indicate that students were satisfied with the quick overview provided by the particles, together with the easily manipulated small cut planes. Challenges were noted with color association and distinguishability. Particles were given dark outlines to improve visibility, and simulated wind movement helped alleviate issues with occlusion. In general, care must be taken that such movement does not misrepresent the data. The visualization included both street-level view and birds-eye view, with participants appreciating both options. However, several features were more suited to expert-users than non-experts, suggesting earlier and more systematic communication with end-users would have aided in balancing complexity.

In summary, this study provides insights, potential solutions, and initial assessments related to 3D-visualization and immersive analytics in urban planning and stakeholder communication. More research is needed to draw generalized conclusions and evaluate the potential of the implemented visualization concepts.

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