Designing an Interactive Visualization for Road Works Coordination using Virtual Reality

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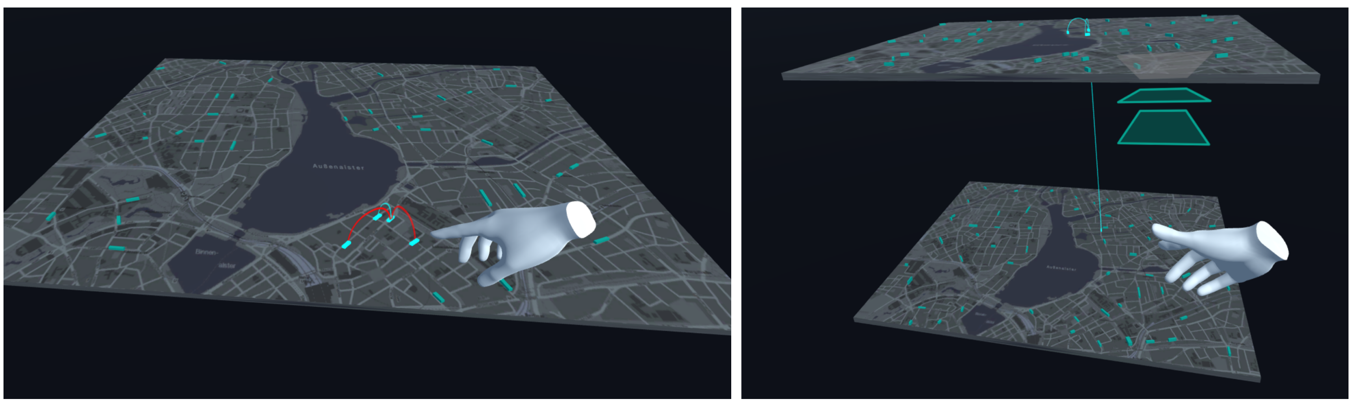

Figure 1: Exploring spatial and temporal dependency data of road works in virtual reality

ABSTRACT

Road works highly affect traffic in major cities, therefore coordination is key to avoid congestion on urban streets and highways. Software tools and interactive visualizations giving insight to complex road works data as well as preexisting spatial and temporal dependencies in between sites are important for the coordination process. In existing 2D visualizations, spatio-temporal dependencies are shown in multiple views, resulting in high cognitive load. In this article we describe the design and evaluation of a visualization using Virtual Reality for exploring multi-dimensional data of road works. The relevance for expert use was reviewed in an interview with local traffic engineers. In addition, a user study was conducted to evaluate the general usability of the prototype. The results reflect an overall positive response and acceptance and show directions for further development.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Information visualization**; Visual analytics; Geographic visualization.

KEYWORDS

virtual reality, data visualization, roadworks, planning, big data

1 INTRODUCTION

The research project iPlanB, a German acronym for 'Interactive Big-Data-Analysis for the Planning of Construction Sites', focuses on interactive data visualizations for traffic engineers in the city of Hamburg. The project's overall goal is to improve the traffic flow by supporting the public sector in road works coordination as well as the planning of traffic light programs and detours using new technologies and user-centered software design. One tool that has already been successfully iterated gives an overview of the city's traffic-related data, including traffic simulation and collection of time-dependent data. By showing a custom overview of all complex data in a comprehensible way suitable to the coordinating process, experts can discover planning weaknesses and get direct feedback.

This work shows an example of how to design and evaluate a virtual reality application for the process of road works planning using a visualization of spatio-temporal dependency data. The main contributions of this work are in giving an example of how to adapt to new technologies in the field of construction site planning. This may also serve as an example for comparable data visualizations in other fields. Additionally, the description of the prototype's design choices and the evaluation process may provide an informative basis for similar projects.

The following work is structured as follows:
section 2 describes the background of the project and the context of the application, section 3 lists related work, section 4 describes the design and development of the prototype in detail. section 5 summarizes the study design of the Usability study and expert interview. section 6 describes the results. section 7 contains discussion of the results and, last but not least, section 8 shows future work.

2 BACKGROUND

In the city of Hamburg the public department of transportation engineering, the *Landesbetrieb für Straßen, Brücken und Gewässer* (LSBG), plans and coordinates more than 25,000 construction sites per year. Coordinating a large number of construction sites that affect traffic is a difficult and demanding task that requires plenty of expertise. One of the main reasons is the underlying complex, multi-dimensional data that need to be considered during the planning process. Traffic-affecting construction sites do not only have a spatial dimension but also a temporal one. This makes the coordination process very complex. Construction sites can affect separate lanes and/or different road sections. Other spatial dependencies are e.g. that a site should not affect or block the detour of a site close by. Coordinated sites can take up to several years or only a few months or weeks to complete. They can be interconnected by different dependencies such as the requirement to take place simultaneously or serially. Giving an overview of all the partially hidden dependencies is therefore essential for successful coordination.

For data management and coordination meetings, traffic engineering experts at the LSBG are already equipped with software offering a 2D map view and a coherent Gantt-chart like timeline giving an overview to all past and future construction sites in the city of Hamburg. An extended version built in our research project also features a view of historical traffic data as well as traffic simulation data.

However, for exploring different variants of temporal and spatial dependencies between construction sites as preparation for coordination meetings, a custom visualization becomes relevant. As for now, finding conflicts in the pool of roadworks data is done at a single user workplace at the LSBG.

3 RELATED WORK

Interactive ways of analyzing spatio-temporal data sets in the context of road traffic were explored by T. Nagel in several publications, e.g. [10, 11]. Visual Analytics [7] is also important in the applied context of spatio-temporal construction site data to help engineering experts in the process of analyzing complex data and conflicting dependencies hiding in-between. Visualizing construction site data in 2D can be done by showing the data on digital maps. Solutions for showing spatio-temporal data in 3D have already been published [1, 15, 19]. In the field of visualizing interconnections between geographic data, a visualization showing flight data between two map layers (departure and destination) by Q. Liu & Y. Teng in [14] shows a straightforward example for working with Big Data on maps. However, showing 3D visualizations on a 2D screen results in overlapping of data and labels. Using Virtual Reality technology allows depth perception in data visualizations, which reduces information overlaps [17].

The use of mixed reality technologies for data visualization in different fields can be found in several research publications [2, 16]. In the field of geographic information systems (GIS) and virtual reality [4], applied use cases can be found, e.g. in visualizing climate data in VR [6] and an application for GIS analysis using Virtual Reality [21]. The use of augmented reality with GIS can be found in several visualizations [5], e.g. for visualizing indoor and outdoor information as prototyped in [9].

For further supporting coordination discussions, 360° panorama views of local sites extend the 2D map view in a realistic, immersive way. A hybrid decision-support system [20] was designed by combining it with the tabletop application that is currently used at the roadwork coordination department of the LSBG. Adding additional data of the site's spatial context using virtual reality received positive feedback by the expert users / target group. However, this system does not (yet) offer an overview of the underlying construction site data necessary for coordination tasks.

A specific approach for exploring the multidimensional dependencies between construction sites as part of the coordination process has not been (fully) covered yet. The following section describes the process of the design and implementation of such an application.

4 PROTOTYPE

The prototype consists of an interactive visualization of multidimensional construction site data using virtual reality technology.

4.1 Concept design

As explained in section 2, the primary goal of the new visualization approach was to show the multidimensional data in 3D space with simple and easy-to-learn interactions, based upon the 2D applications currently used at the public department.

To achieve this, we altered the design by Q. Liu & Y. Teng in [14] using map layers as different points in time. Location based dependencies can be identified on each map layer individually. Time series related dependencies are represented by connections between the layers. An example for the field of roadworks coordination is the following: a construction site in 2022 needs to be finished before another site, which was planned to begin in year 2028 in the far future and which is therefore shown on the future, above layer. There is a connection shown between the two map layers in neutral color indicating that there is no temporal overlap. However, if the actual construction time of the site in 2022 will extend considerably, a temporal overlap will cause a conflicting dependency state which results in a warning color visualization of their connection. This visualization can also be used for multiple dependencies, as shown in figure 2.

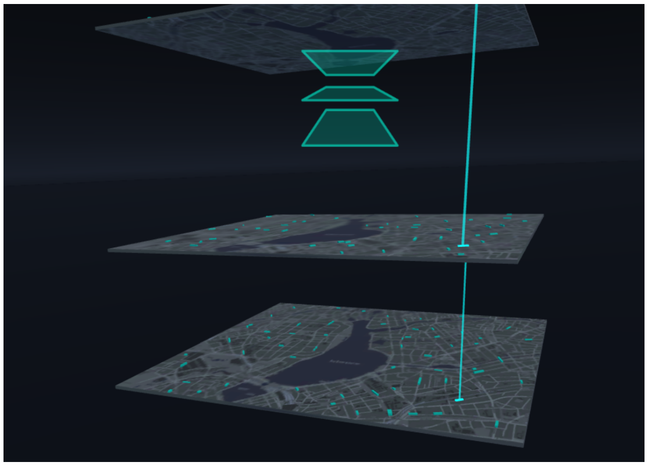

Figure 2: Several map layers representing points in time

4.2 Implementation

As explained in section 2, identifying conflicting roadworks is a single user workplace at the given time. We therefore decided to use a virtual reality display for visualizing the 3D content in a highly immersive, non-distracting environment, allowing intuitive, six degrees of freedom (6DoF) interaction. For reasons of mobility and comfort, we used the Oculus Rift system[1]. Another positive aspect of this system is its comparatively low price, which makes it more affordable for public departments which often have a small budget.

The described visualization was implemented using the game engine Unity[2]. Whereas VR functionality is a native part of the game engine, the Oculus SDK[3] was imported for direct functionality and 3D representations of the Oculus Touch controllers.

The core functions of the prototype include a set of representative construction sites with coherent temporal and spatial dependencies on three map layers (interactive map, previous time layer, far future time layer) and basic interactions supporting exploration tasks.

4.3 UI & Interaction Design

The colours in the visualization were chosen advisedly: The construction site data cubes are represented by cyan, the main color of the user interfaces of the Oculus system. The map design was adapted from the former 2D application described in the last section. The dark theme avoids eye strain caused by the eyes being exposed to large light areas in virtual reality displays.

One issue found early in the iteration process was the overlap of map layers in the first-person view. Especially when the user zooms into a small area of the city, other map layers can be completely out of sight or overlap with the current layer. To notify the user on visible connections with sites on other map layers, a small UI widget displayed in the upper area of the field of view indicates multiple layers (see figure 2). It is anchored to the movements of the head and therefore always visible in the view field when notifying the user of the appearance of dependencies to sites on other map layers.

Figure 3: Selecting sites by pointing with the index finger

Basic interaction techniques we have implemented are selecting construction sites, rotating and zooming in and out of map layers and selecting sites for displaying/hiding connections, illustrated in figure 4).

Selecting a construction site is implemented by extending the left or right index finger in the direction of a construction site and touching it (see figure 3). For notifying that a construction site was successfully selected, the respective data cube is highlighted and the controller in the respective hand responds with subtle vibration as tactile feedback.

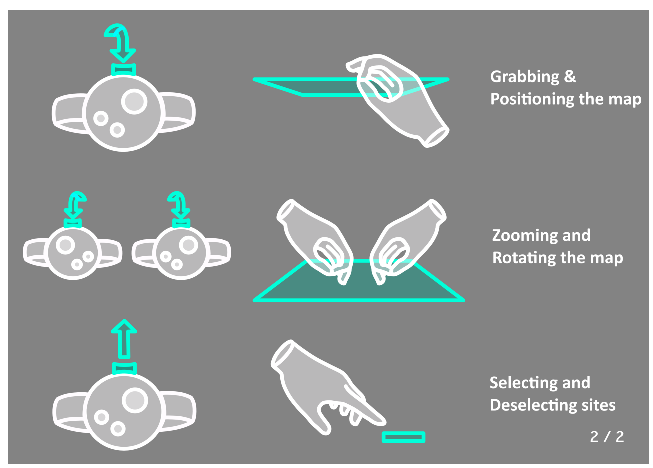

Figure 4: Available interaction controls and assignment of buttons

By touching a map with the controllers and pushing the Trigger buttons of both controllers, the map can be grabbed to alter the size and the rotation of the map (see figure 4). The implemented movements are similar to zooming and rotating with two fingers on a 2D touch device. Zooming in is implemented by moving the

[1]Oculus Rift, https://www.oculus.com/rift/
[2]Unity game engine: https://unity.com/
[3] https://developer.oculus.com/downloads/

hands away from each other and zooming out by bringing the hands closer together. By moving the hands in a circular motion, the map is rotated.

Grabbing the map by pressing the Trigger button on one or both controllers close to a map allows moving the map. In this mode, the map can be moved horizontally to move around different map areas or see the map layer(s) from a distance. Besides, the map can also be moved vertically to follow temporal connections and reach the map layer above or below the grabbed map.

5 USER STUDY

To evaluate the usability and relevance of the prototype for the applied case of identifying conflicting roadworks, we designed and conducted a test session plus interview with an employee of the LSBG and a small usability study. Both focus primarily on qualitative user data.

5.1 Theory and Design

First of all, the usability study was performed to find out if major usability issues exist. A catalogue of 9 tasks was designed to represent real world coordination tasks in order to examine Usability and comprehensibility. The list can be found in the appendix **??** and was also used in the later expert interview at the LSBG.

To evaluate usability issues, we decided to use the Thinking Aloud method [13]. The Thinking Aloud method is an effective way to evaluate usability issues through verbalization of thoughts and feelings, as well as observing subjective impressions. According to J.Nielsen [12] around 5 participants are required to detect up to 77-85% of usability issues during a Thinking Aloud test.

To measure usability in a quantifiable way, the System Usability Scale (SUS) [8] was administered after the test session. To measure the occurrence of distractions and the overall quality, a questionnaire for investigating Presence was used. For the overall presence participants experienced in the virtual environment, we chose the Presence Questionnare (PQ) of Wittmer and Singer [22]. As the prototype does not have audio, the respective question is cut out — resulting in a total of 19 items for the PQ. For evaluating negative physiological effects, the Simulator Sickness Questionnaire (SSQ) [18] was administered. All of the questionnaires had been carefully translated to German language for better understanding.

In the test session and interview with the coordinating staff, we used the same tasks for an in-depth view of the prototype. Also, a semi-structured interview was prepared for collecting feedback and rating usability, presence and physiological effects.

5.2 Participants

In the Usability study, seven participants (age from 21 to 31, M=24,2) took part in the experiment. They were chosen wisely: 2 already had experience in the domain and workflows of coordinating construction sites at the LSBG, as they were corresponding closely or regularly with the roadworks department staff. 5 participants had prior knowledge in interaction design as part of their studies. 5 participants already had prior experience with Virtual Reality devices. 2 participants had never used VR devices before the experiment, which is probably representative of LSBG employees.

The employee interviewed last, who is responsible for roadworks coordination in the city of Hamburg, already has several years of experience in the construction planning sector at the public department. They had minor experience with virtual reality devices.

5.3 Apparatus

The usability study was conducted in the HCI lab at the computer science campus (Informatikum) of the University of Hamburg. As equipment, we used an Oculus Rift system connected to a standalone PC with a Nvidia high-end graphics card. For video and audio recordings we used Open Broadcaster Software Studio (OBS Studio)[4].

The expert interview was performed in the facilities of the LSBG. Therefore the hardware setup was slightly changed, using the Oculus Rift system with a VR-ready laptop[5]. Equipped with a 16GB RAM and a Nvidia GTX 1060 graphics card, the notebook does not cause performance issues when running the application, however, additional video recording is technically unfeasible. Therefore, video recording had to be replaced by a smartphone based audio recording and note taking during the session.

Figure 5: Mobile setup in the facilities of the public department

5.4 Procedure

First all participants of the usability study need to sign formal documents due to the data policy agreement for recording audio and video. Next, they are asked to fill out the following questionnaires on a separate notebook: a questionnaire for collecting demographic data and the first part of the Simulator Sickness Questionnaire [18].

Afterwards, the use scenario of the application is explained in depth. A short story about the duties they will take on as a construction site planner is read out to them (see appendix A). In this way, participants get relevant information about the overall process of site coordination.

[4]Open Broadcaster Software Studio: https://obsproject.com/
[5]Razer Blade laptop: https://www.razer.com/gaming-laptops/razer-blade-pro

Afterwards the Thinking Aloud procedure for collecting qualitative information about the prototype is explained. Next, the participant are told to put on the headset. To train the Thinking Aloud method, the Oculus Home screen is shown to the participants and they are asked to look around and describe what they see, think, feel.

After 1-2 minutes, the prototype application and the audio and video recording are started. At first, all construction sites are hidden and the participants do not yet have the controllers. They are instructed again to comment on what they see, think and feel, if they do not already do so.

In the next step, the participants receive both controllers and are shown how to display the help pages (i.e. by clicking on the thumb stick). They are encouraged to try out the different interaction techniques and familiarize themselves with the system before the tasks start. Afterwards, the construction sites are displayed and the 9 tasks (see appendix **??**) are announced. Participants are instructed to ask questions if any information was not understood clearly or forgotten while solving the task. Participant are told to solve the tasks independently, with help only being provided to them if they are stuck to prevent result alterations.

The procedure continues with the tasks. All tasks are read out loud one after the other and subsequently solved by the participant. As soon as the participant gives the correct answer, the text task follows.

In the following, with the VR headset still on, the interviewer asks as set of questions about the overall experience to give the participant opportunity to give individual feedback. After this, participants are are asked to remove the headset and the recording is stopped.

For the final step, the participants fill out the following questionnaires: the 2nd part of SSQ [18], SUS [8] and the 22-item Presence Questionnaire [22].

Figure 6: Usability study in the lab of the HCI group

In the expert session for validating the application's relevance, the written questionnaire parts were excluded and some questions administered verbally. The introduction part was cut as the participant already has deep knowledge of construction site planning and the coordination process. The prototype was then tested by completing the same tasks (see appendix **??**), but in random order. Afterwards a semi-structured interview was conducted including questions about the relevance of the prototype content for everyday coordination tasks. Also, missing information and future development iterations are addressed.

5.5 Limitations

The presented first iteration of the application has only limited data, e.g. a small dummy set of construction sites, three time layers and three types of temporal / generic spatial dependencies. In real world scenarios more types of dependencies occur, such as organizational dependencies in the same construction project or sites influencing the same traffic flow into / off the city. Also, more construction sites to be explored for conflicting dependencies should be implemented. At the given date, only small regions around a specific construction site are investigated for conflicts. Therefore the implemented small data set is a valid representation for current coordination tasks.

The prototype only implements basic interactions such as zooming, rotating and navigating around the map. The map shows the center of the city of Hamburg, whereas exploration of the whole area of the city is not (yet) implemented. However, with the implemented way of zooming (see section 4.3), the default view can also cover the whole area of the city and every area can be reached with the same interaction technique.

Limitations in the quantitative evaluation are the Usability study's very small sample size, therefore the results of the questionnaires can only be conditionally considered as representative. They are only useful in combination with the qualitative results. They may also allow for more honest feedback, as the participants fill it out anonymously.

6 RESULT

In the following, the results of the user study and the interview are presented. The focus in this paper is mainly on the qualitative results from the Thinking Aloud procedure.

6.1 Qualitative Feedback

With recordings of 7 sessions, a total of 208 min = 33,5 h of video and audio recording was collected. The written transcripts were divided into parts of task solving process (introduction and task specific information, e.g. answers to task) and comments on the application (experience, interaction, design). The each participant's comments were extracted and roughly grouped using the same pattern, i.e. by 10 major topic categories including a total of 9 subcategories:

(1) Physical / ergonomics
(2) Interaction with environment
    a General
    b Navigating
    c Rotation
    d Scaling / Zoom
    e Selection of sites
    g Haptic feedback
(3) Hand avatars
(4) Map Layer
(5) General visual design
(6) Interpretation
    Color coding
    Temporal dependencies

(7) Layer widget
(8) Help function
(9) Readability
(10) Emotional level

Within these categories, several similar statements between participants on each topic could be found. These were merged and resulted in a total of 33 single statements, sorted by the number of participants giving this sort of (positive) feedback and the number of participants commenting the opposite. Participants sometimes gave mixed statements during one session, e.g. as they developed necessary skills over time and therefore commented differently at the end of the experiment.

By transcribing the material, many similar statements between the participants were found and analyzed. The readability, in detail the blurry and unfocused view was mentioned by the majority of the participants. However, this seems like a mostly technical problem in regard to the display resolution of the implemented hardware system. To improve the general pixel resolution and thereby also the readability of text within the application, new VR systems with higher display resolution than the Oculus Rift CE should be used.

The statements referring to the general interaction were: good, funny, intuitive, natural and fluid. These can all be rated as positive regarding usability. 5 of 6 participants gave this statement. This indicates the prototype's interaction design goes in the right direction. Therefore making crucial changes to the interaction design is not recommended. The reason why 1 participant described the Scaling/Zoom interaction as negative compared to the transcript is that they always triggered scaling and zooming at the same time even though the participant only meant to perform one action. Using two separate keys on the controllers for the interactions might be a simple but effective solution.

Another issue concerning readability is small or blurry road names. However, 2 participants stated that road names are well readable later in the test. Compared with the transcript, 2 participants commented that they cannot read the names properly but directly afterwards found out how to zoom and thereby reached a detailed map view. It is advisable to explain zooming at an earlier point in the application (or improve zooming) or trigger the change to the more detailed map texture at an earlier level of zooming.

Additionally, *meaning of depencendies unclear* in the category *interpretation* shows that it is necessary to improve the the data visualization of the prototype. One way to this this might be by adding a map legend that is always visible in the field of view. Also when adding more (diverse) data, a legend will become essential. Other reasons for the number of statements regarding interpretation could be that novice participants struggled with the unfamiliar and complex context of construction site planning and thereby misunderstood parts of the visualization - as the expert in general did not have problems with understanding the meaning of the dependencies.

Statements given by only one participants were also interesting, but not rated as important as issues the majority of participant found. However, for future development (when most important issues are already tackled), a complete list of all findings and ideas might become useful.

The interviewed employee from the LSBG gave similar feedback on usability during the Thinking Aloud session. Several positive and negative comments on interaction, readability and comprehension were made. Compared to the participants of the usability test, the expert did read out streets considerably more often. The expert showed a general awareness for and interest in the road networks in the area around any construction site. All in all, the expert rated the prototype as *important*, and a *good option*. He/she believed that visualizing in virtual reality and 3D made road construction planning more accessible, and also more *enjoyable / attractive*. In addition, the expert supposed the dependencies were displayed more understandably, and thus *totally practical for externals without background knowledge*. For illustrating the relevance of the prototype for real world usage, the expert stated missing detour routes and building times. He/she described the prototype as an intuitive, comprehensible and simple version of the visualizations used at the given time. These aspects were rated as valuable for explaining coordination to new employees or less trained colleagues / visitors at the LSBG.

6.2 Quantitative analysis

The questionnaire data of one participant was not considered due to technical issues, resulting in 6 records.

For the Simulator Sickness Questionnaire [18] the corresponding z-values for all 16 symptoms were calculated and compared with the data used in [3]. There were no significant deviations from the data we calculated using [3]. Derived from this, simulator sickness probably plays no role in the use of the prototype. This also shows the fact that participants did not report physical symptoms correlated to simulator sickness during the Thinking Aloud session.

By analyzing the System Usability Scale [8] the mean score over all records was 86,7 (SD=5,4) in percentage. Lewis and Sauro [8] used a percentile mean score of 68 over all records, and established a general classification from A to F according to the resulting score value. According to the rating system, our prototype with a rounded mean of 87 is classified by A, which is equivalent to the highest rating.

For our variant of the Presence Questionnaire [22] we calculated all z-values and standard values of all dimensions except *Haptic*. The values were compared to the standard values of the questionnaire as a general aggregate. We came up with significantly higher mean scores for all dimensions except for *Realism*. As the visual representation in the prototype is an abstract visualization and non-realistic, this result is self-explanatory. The mean value of 24 (SD=3,54) for the dimension *Haptic* could be compared, conditionally, with the Thinking Aloud result of the category *Interaction - Haptic feedback* which was positively stated with *Haptic feedback & vibration good extension* by two participants.

7 DISCUSSION & FUTURE WORK

Although the results depict an overall positive reaction and acceptance, there are still some limitations (see section 5.5) and usability issues. As the described prototype focuses on the basic presentation of temporal dependencies and interactions with the map, detailed data of construction sites are not yet implemented. The currently purely visual, non-textual representations of the planning scenarios and time dependencies should be extended in future alterations.

Up to the given date, as we leared from in our conversations with the engineering staff at the LSBG, the exploration process is mainly an organizational task realized as a one-person workplace. However, as internal organization structures and workflows in the department may change, supporting collaborative work in the application by adding multi-user support might become necessary in the future.

However, as soon as the missing two types of data are implemented, the interactive VR application will offer not less than the same insights to users as the existing 2D application, and make the coordination process more *'compelling'*, as commented by the LSBG staff. Using an interactive VR visualization in the context of road works data needs several iterations to develop into an application assisting everyday coordination tasks. Targeting the issues found in our study and implementing the listed improvements of the application in another iteration will lead the way to an exciting, useful application for future road construction planning and coordination.

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(removed for anonymous submission)

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APPENDIX

A CONTEXT EXPLANATION

The following tasks were used in the user study and can also be used to explain relevant use cases during the demonstration of the application (translated to English language).

(1) Find the construction site at street Grindelhof near the university.
(2) Select the construction site at Grindelhof and explore which construction sites it is connected to before the year 2022 when it is planned.
(3) You are planning construction sites left of the Alster (entire left map section). Count how many construction sites in that area are related to construction sites in the year 2022.
(4) Navigate to the Feenteich on the Northeastern part of the Alster. Choose the construction site in Herbert-Weichmann-Straße, in Schöne Aussicht and in Auguststraße. Find the site with the most dependencies on other construction sites (all planning years).
(5) Find the construction site in the Southeast of the map which has both dependencies on construction sites before and after the year 2022.
(6) Navigate to the construction site at the intersection Bachstraße - Beethovenstraße in the Northeast of the map. Find the construction site which needs to be completed before the construction in 2022 can be started.
(7) Find the construction site in the area south of Planten un Blomen with conflicting dependencies on construction sites which are planned after the year 2022.
(8) A construction site in 2021 should gradually renew the complete street pavement in the given area. However, in 2022 four new construction sites are planned in which the pavement would be renewed again. These construction sites are: Grindelhof, Hallerstraße, Rotherbaumchaussee, and in one blind alley on the Grindelallee.
(wait until found) Find the construction site in the year 2021 that all four construction sites depend on.

(9) You are interested in the construction site located in the Southeastern part of the Außenalster in Lange Reihe because in this area there are many dependencies on construction sites of the same year. Find this construction site.
(wait until found) Find all construction sites that are directly or indirectly dependent on Lange Reihe. Count how many construction sites in the scenario must be coordinated if the site in Lange Reihe would change.
What needs to be considered in the coordination process?