The Potential of VR-based Tactical Resource Planning on Spatial Data

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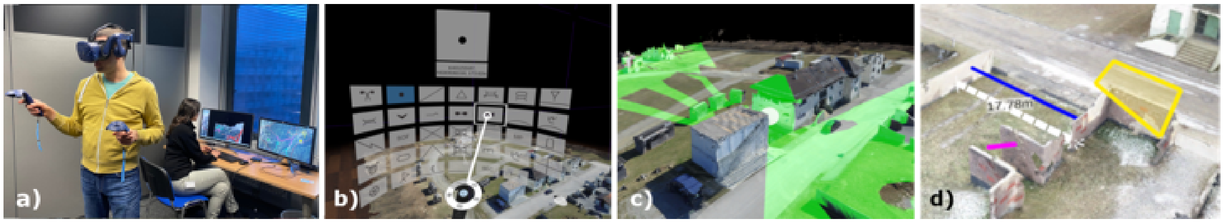

Figure 1: The scope of functions of our prototype for tactical resource planning includes: **a)** an asymmetric collaborative setup, **b)** NATO symbol placement and composition, **c)** line-of-sight visualization and **d)** distance measurements.

ABSTRACT

Planning tactical operations on topographic maps, for rescue or military missions, is a complex process conducted by interdisciplinary experts and involves the time-consuming derivation of 3D information from 2D maps, mostly solely executed by experienced professionals. Previous research repeatedly showed that virtual reality (VR) can convey spatial relationships and complex 3D structures intuitively. In this work, we leverage the benefits of immersive head-mounted displays (HMDs) and present the design, implementation, and evaluation of a collaborative VR application for tactical resource planning on spatial data. We derived system and design requirements from consultations with domain experts and observations of a military on-site staff exercise, a simulation-based training aiming to strengthen rapid decision-making and teamwork during a time of crisis. To evaluate our prototype, we conducted semi-structured interviews with domain experts who organized and observed field tests at different military staff exercises. The interviews support the proposed design of the prototype and show general design implications for planning tools in VR. Our results show that the potential of VR-based tactical resource planning is dependent on the technical features as well as on non-technical environmental aspects, such as user attitude, prior experience, and interoperability.

Index Terms: Computer Graphics [I.3.7]: Three-Dimensional Graphics and Realism—Virtual Reality

1 INTRODUCTION

A staff exercise is a simulation-based training aiming to strengthen teamwork, communication, leadership skills, and decision-making in critical situations [24, 28] commonly executed to train high-level military personnel [24] or professionals working in a critical infrastructure [40, 52]. The objective of a military staff exercise is tactical resource planning for unpredictable events, natural disasters, war, or cyber attacks [24, 25].

The landscape of a mission site has a great influence on tactics and can constitute unexpected obstacles. Analog terrain models of the operational site, such as elevated maps [7], 3D terrain models, and standard 2D paper maps are commonly used in a military staff exercise to support tactical resource planning and logistics. Some problems of analog equipment are the lack of intuitive transfer of spatial relationships and geographical structures, and the absence of the third dimension. Users often rely on depth cues communicated through shading or visual cues about the terrain topology to derive 3D information [2, 24]. Therefore, only experienced users are able to obtain line of sight, height judgment of ground elements, and quantitative information, for instance, distances and slope, effectively and rapidly. Tactical planning for mountainous landscapes, such as in the Alps, can be better performed on a 3D representation than on traditional, flat maps [2].

A large body of work presents numerous digital planning environments, inherently providing computer-supported analysis and presenting interactive 2D or 3D representations of the terrain [2, 5, 12, 16, 58]. Nonetheless, little attention has been paid to the role of immersive tools such as Virtual Reality (VR) and how to efficiently design user interactions for tactical resource planning. A well-known advantage of immersive environments is the intuitive spatial understanding due to a higher sense of presence, 3D perception, and realism while fully immersed [6, 27, 48]. Previous research suggests that higher immersion leads to a more realistic perspective on a given 3D space [10]. Furthermore, visualizing spatial data in VR, compared to 2D desktops, improves the perception of structures with complex geometry [27, 48]. For instance, VR has been effectively used for flood preparation management [32], for spatial planning tasks, such as urban city design [29], and collaborative planning environment for space missions [17]. In immersive spaces, users understand a task through unique viewpoints or can recreate an immersive experience to prepare and support decision-making [46].

Although the empirical benefits of immersive environments on spatial understanding are evident, they are not yet systematically evaluated in the context of planning operations using spatial data for rapid decision-making. Immersive spaces for tactical resource planning could combine the advantages of current digital tools and the unique perspective when using a VR headset. To close this research gap, this paper aims to address the following research questions:

- Q1: *What potential lies in VR-based tactical resource planning using spatial data?*
- Q2: *How can we design VR applications to facilitate efficient tactical resource planning on spatial data?*

In this work, we describe the design process and implementation

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of the prototype based on state-of-the-art literature and in-depth requirement analysis. The overall scope of operations is derived from consultations with domain experts and a field study. During the field study, we observed an on-site military staff exercise that led to the design and system requirements for the prototype. We used a qualitative evaluation approach to answer our research questions. We conducted semi-structured interviews with three geographical specialists who have been providing geographical information products for staff exercises for decades and observed field tests of our prototype.

Our results provide important insights, which can aid to advance the understanding of the potential and design of VR-based tactical resource planning tools. Our major findings are:

- VR-based tactical resource planning applications should be developed to solve sub-tasks of the planning process where VR is the most useful and advantageous in comparison to available alternatives.
- Our results confirm that features for terrain annotations and quantitative analysis, such as terrain measurements, are essential for tactical resource planning tasks on spatial data.
- The potential of VR solutions for tactical resource planning in a staff exercise depends on environmental factors, such as the user attitude towards technology, interoperability of the system and the previous experience of the users.

Our work contributes to the existing body of research by *showing how VR systems could support team decision-making in the context of a military staff exercise*. We present an *analysis of current digital solutions*, describe the *design decisions for a VR prototype developed for a military staff exercise*, and derive *guidelines for designing an immersive space to facilitate efficient tactical resource planning support*. Additionally, we show some important insights into the early-stage design process of VR-based tactical resource planning tools and can assist other developers and scientists who investigate the role of immersive Geographical Information Systems (GIS)s for urban planners, incident management, mission planning, and emergency preparation training.

2 RELATED WORK

The tasks rehearsed in a military staff exercise are executed on a specified mission location, therefore accurate spatial information about the site is crucial. Spatial data help staff to familiarize themselves with the terrain and surrounding infrastructure [52] before mission execution, plan tactics and logistics in the field, and make rapid decisions about operational maneuvers. People engaged in designing tactics use tools when seeking support for decision-making, communication, terrain analysis, or note-taking. Digital planning tools offer several benefits compared to analog equivalents, such as the option to save planning states, effortless repetition of training scenarios, visualizing a common mental concept, no physical boundaries, and increased engagement. This section addresses current literature presenting the design of digital tactical resource planning applications used in the context of staff exercises or mission planning and rehearsal, as well as broader research work related to ours, such as collaborative systems and team decision-making.

2.1 Digital Tactical Resource Planning

Digital tools for tactical resource planning presented by state-of-the-art research can be grouped into three categories: (I) desktop-based, (II) projection-based, and (III) headset-based. The first group, desktop-based tools, present 2D or 3D data on a 2D display, projection-based tools augment a physical object using light projections and at last, headset-based tools provide insight on spatial data in a partly or fully immersive setup.

Desktop-based Tools

A GIS is a well-established desktop-based technology and allows users to process, visualize, analyze, interact and quest geographic information over time using a base map and additional information layers on top, related to the problem space [4]. Figure 2, derived from previous work, presents an example in the context of flood emergency management [20]. Flood zones and critical facilities are derived from the geographical land data. The derived data is then used to highlight facilities vulnerable to floods. In a staff exercise, geoanalysis products, commonly generated by a domain expert using GIS, support decision-makers. There is a broad range of different GIS software, libraries, and services available [14, 21, 35, 42].

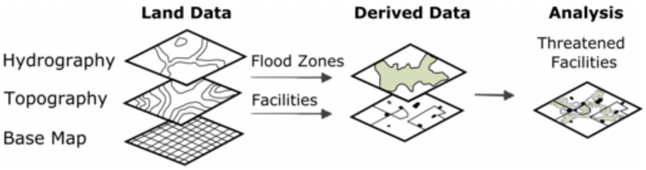

Figure 2: Using multiple layers of geographical information and visualizing the proximate infrastructure helps to analyze threatened facilities in a time of crisis. Image derived from Gunes and Kovel's work [20]

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Stanzione and Johnson [53] developed a desktop-based tactical planning tool based on ArcGIS [14], called *GIS-Enabled Modeling and Simulation (GEMS)*. The objective of GEMS is to facilitate digital mission planning and rehearsal, enhance situation awareness, and enable modeling, simulation, and visualization systems directly on the terrain. Implemented functions were line-of-sight calculations for targeting or communication, parameter queries from the elevation data, path planning or obstacle avoidance, terrain skin adjustments, and placing additional elements on the terrain, like simple geometries. Other research work based on GIS use alternatives to 2D monitors, like tablets or other handheld devices. Mobile GIS-based planning tools [8, 9] implement similar features for tactical planning, such as point-of-interest selection and labeling. The processing power of mobile tools is limited and the scope of operations is reduced, but they are location-independent and can therefore be carried to a mission site.

While GIS systems provide a comprehensive scope of operations, most applications do not provide intuitive 3D information. Inexperienced users have to invest more time to understand the topology of the terrain environment from a 2D terrain presentation. 2D displays offer a 2D impression of a 3D environment, while immersive displays transfer true depth information.

Projection-based Tools

The modern alternative to analog military sandtables [7] are projection-based tables that blend the virtual content with the physical environment. Projection-based tools in the military context were already discussed by Alexander and Gärnter [2]. They proposed a system using a mirror-based projection on a flat surface. Users perceived depth information from the projected data using shutter glasses and were able to manipulate virtual objects. Modern versions of these sandtables are tools such as OrMis [5] and ARES [7]. Research work evaluating projection-based tools conclude that 3D cues, such as provided by elevated maps or sandtables, enhance user engagement and reduce workload [7] [23]. Schmidt-Daly et al. [47] analyzed different tools for spatial knowledge acquisition and spatial reasoning skills. In their study, three experimental displays were compared, a paper map, a 2D map on a computer screen, and a 2D map projection on a sandtable. They observed that participants that used the sandtable achieved better results for landmark identification and distance estimation tasks. Another advantage of 3D maps is the visualization of vertical information of data points. The visibility of the third dimension allows us to understand the landscape and topology more intuitively.

Projection-based planning tools provide more evident 3D information, but the benefits, similar to desktop-based solutions, mostly depend on the depth perception and experience of the user. Fully immersive tools could present 3D data more intuitively, independent of prior user experience. Further, projection-based tools depend on a physical table, physical 3D model of the mission site and additional hardware for projections.

Head-Worn Displays

Head-worn displays provide unique viewpoints on data and true depth information. This is either realized with Augmented Reality (AR) or VR head-mounted displays (HMDs). Research about the combination of GIS and VR technology, also called VR-GIS [22], emerged in the mid-1990 and past studies show that VR-GIS improves the spatial understanding and perception of structures with complex geometry, as opposed to standard desktop monitors [48] [27].

VR is used for military purposes since decades [33, 34] and range from immersive simulated battlefields [11, 56] to stress management [39]. In the context of mission planning and rehearsal, there is limited research on how immersive systems could support decision-making and tactical resource planning on spatial data. Further, how user interactions are efficiently designed in VR-based planning tools.

In a preliminary study, Alexander et al. [1] investigated the potential of using immersive headsets during the briefing and debriefing process of air force mission planning. An AR prototype is used collaboratively for the briefing phase, leveraging the benefit of a see-through HMD, while VR is used for the debriefing phase to recap mission events on spatial data. The authors determined that VR may support the evaluation and performance assessment of air force missions after execution, but in-depth user studies are necessary to confirm this.

With this work, we want to contribute to the current state-of-the-art by presenting our VR prototype design and general design implications for tactical resource planning tools.

2.2 Designing Collaborative Environments

Tactical resource planning involves the experience of interdisciplinary teams and is a collaborative task. Digital Collaborative Virtual Environments (CVE) transform a digital environment into a rich 3D space in which multiple users can interactively navigate, communicate and share a given context [46]. Characteristic features include the choice of viewpoint and movement in the virtual space, access for multiple users simultaneously, different types of input for communication, user embodiment, mutual interactions with virtual objects, different meeting and interaction scenarios between users, adaptive broadcasts of information, and balance of power, like an active speaker or listener [51].

A central feature of a collaborative space is *communication*. Users communicate with others in immersive VEs either through direct channels, as audio input and output, or through non-verbal communication cues, using their surrounding space, with gestures, body language, and facial expressions [57]. Visual cues, such as primitive geometries, gestures, user embodiment, and user attention indicators [46], allow effective conversations in CVEs and increase the awareness factor [31]. Common visual cues for sharing awareness are ray-casting, visualizing or extending the gaze of the user, sharing the view frustum [41] or virtual sketching [30]. If users work together in VR, hand tracking can be further used to share attention and awareness with others [45]. Ray-casting is widely used to indicate attention [3] and facilitate object manipulation [43].

The type of collaboration varies depending on the use case and available hardware and can be categorized in time, synchronous vs. asynchronous, and space, remote vs. on-site collaboration [37]. On-site, also co-located, collaboration can be grouped in symmetric and asymmetric collaboration. In a symmetric setup, all users wear one headset type, for instance, either an AR or VR device. A setup where users in a collaborative system wear different headsets or use other mediums, like a desktop monitor, is called asymmetric. Users using a non-immersive medium usually interact with objects in the VE through a touch-sensitive display or peripherals [18, 19]. Su et al. [54] use an asymmetric collaboration approach for immersive data analysis. Users can choose between visualizing the data in 2D or 3D. With this approach, the authors aim to reduce cognitive load and enhance the data analysis outcome. For our prototype, we leverage the benefits of an asymmetric collaborative setup to support different user roles and objectives and this will be further discussed in the methodology section of this paper (Section 3).

We further aim to design a VR prototype to support the team decision-making of staff exercise groups. In a broad spectrum of industrial applications, there are efforts to use CVEs for decision-making [15, 49, 49]. Numerous factors influence decision-making in CVEs, for instance vision, experience, politics, emotions, and others. Digital tools and simulations are used to identify the character of a situation or problem, aiming to optimize those processes concerning the outcome [38] and the objective is to provide a comprehensive perspective on a task or to recreate a real experience and to prepare or support decision-makers [46]. Roupé showed that two main factors are influencing the efficiency of communication and decision-making in immersive environments [44]: human information processing, like reasoning, spatial perception, the background of the users and task goals, and technical aspects of the system, display type and degree of immersion. The system accelerates the decision-making process by providing a broader understanding of spatial structures and their interactions with their surroundings. Small deviations or latency concerning the portrayed information in CVEs could lead to suboptimal results and a decrease of the benefits [13] of the system.

In this work we derive our design requirements by observing current decision-making and communication processes in an on-site military staff training to digitize those process in an optimal way.

3 METHODOLOGY

To investigate the potential and identify user features for VR-based tactical resource planning tools in a military staff exercise, we decided to develop a prototype. The next sections present our design process and technical setup, as well as our study design to evaluate the prototype.

3.1 Requirement Analysis

The design of our prototype should reflect the fast-paced environment of a military staff exercise. This section describes our consultations with military geodesy experts and our observations at a field study to derive requirements for VR-based planning.

3.1.1 Expert Consultations

In the first design phase, we undertook initial consultations with experts of the Institute of Military Earth Sciences of the Austrian Army. The basic technical requirements were discussed: the data format and structure of the terrain data and additional data to export/import terrain annotations, as well as the geographical reference system (UTM). After, we attended an on-site military staff exercise and conducted a field study to understand current procedures and structures in a staff exercise.

3.1.2 Field Study

The field study took place at the beginning of a two-week-long staff exercise and lasted three days. The goal was to passively monitor the behavior of the officers in training, their way of communication, group dynamics, and planning process. At the end of each day, we had short interviews with participants familiar with the processes and the structure of a staff exercise.

The training was executed in a large room, separated into several working areas equipped with numerous paper maps of the operational area, tables, chairs, and digital support tools, for instance, printers and computers. Each working area was dedicated to the staff of one discipline, for example, intelligence or logistics, and every staff had to solve complex problems in their field of expertise in the given fictitious scenario and report to the operational leader, the commander. People in charge use the results reported by the groups to translate them into actions against a high-pressure deadline. Figure 3 depicts the timeline of the observed staff exercise. The schedule continuously repeats four phases: a planning phase, followed by a briefing, mission execution, and debriefing phase. Depending on the tactical task, one cycle can take from 24 to 48 hours.

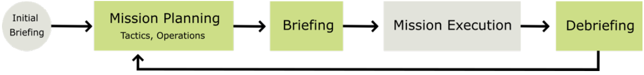

Figure 3: The abstract timeline of the observed staff exercise.

Mission Planning: During the planning phase, groups work in their dedicated section of the room and use different tools, such as computers or paper maps, for planning. This phase aims to gather information about a given scenario and plan actions to solve a tactical task. A typical output is an annotated transparent plastic sheet pinned to a paper map of the application environment. The annotations on the sheet visualize point-of-interests, paths, notes, areas of opponents, allies, or other agents and describe the strategy for the given context. Part of the tactical resource planning process is terrain analysis and investigation of the local situation. The terrain influences the annotations and placement of involved mission agents.

Briefing: In this phase, all groups come together and present their strategies to the other groups and the commander. The annotated transparent sheets of each group are overlaid on the paper map of the operational site. The commander provides feedback, gives advice, and orders instructions to each group according to the presented plans. The commander might ask the officers in training about terrain characteristics, visibility, and other information regarding the presented strategy. Some examples are: *"How long does operation group A need to walk to position X?"* or *"Can operation group A see point X from position Y?"*. Additionally, the commander comments on strategies according to his experience and continuously points out points-of-interests on the map, such as *"Our ally B at this position might decide to go this way."*.

Mission Execution: Depending on the military staff exercise structure, the mission execution is rehearsed by soldiers in a training environment related to the scenario or invented by agents involved in the training organization.

Debriefing: During debriefing, all groups and the commander in chief analyze every event during mission execution and their results. The commander discusses the successive steps and further tasks for the next mission planning iteration.

From the observed activities, communication between staff, the overall structure of the staff exercise, and insights derived from related work, we extracted two key use cases for the VR prototype design: **I) terrain annotations** and **II) visibility and quantitative analysis**. The first use case, terrain annotations, allows users to add information, such as sketches, lines, markers, and text, to the base map of the operation site. Tools for visibility and quantitative analysis help the trainees to extract pivotal information from the 3D terrain model, such as distances, measurements, and line of sight. With our design, we want to build on previous research showing the capability of immersive collaborative spaces to support team decision-making. We decided to use an asymmetric co-located collaborative setup, similar to [54]. Two users can interact with a virtual terrain synchronously using the same instance running on a local computer, one from a 2D display and the other one using a VR headset. This way we introduce the technology into their current processes gradually and allow different user roles, for instance a presenter in VR and planner on the desktop. For this work, remote collaboration is not necessary because the military staff exercise takes place in the same physical environment (see Figure 1.a).

3.2 VR Tactical Resource Planning System

We present a technical design of a VR system tailored to tactical resource planning and further describe the implemented interaction metaphors for collaboration and object manipulation in immersive 3D spaces for terrain analysis and tactical resource planning.

3.2.1 System Overview

We used the game engine Unity3D and a collective of other software libraries for specific rendering tasks, such as vector graphics and GPU instancing. A 3D terrain imported into our prototype, consists of three data types: *geographical data (.obj)*, the data for the 3D terrain , *project data (.json)*, used to define the details of the geographical data, and *layer data (.csv)*, representing the annotations created by the user. Figure 4 shows the main components of the hardware and software system and describes the general data and information flow. We developed our system using an off-the-shelf VR headset, the HTC Vive Pro.

Both users can see the same instance of the 3D terrain, but use different mediums and interact with different UIs. One challenge is to avoid occluding large parts of the 3D terrain. On the 2D desktop interface, we provide an interactive topographic map view, an iconic menu for access to the main functionalities, and additional visual information, like a north arrow. If the desktop operator selects a point or an object on the terrain, we show quantitative properties of the selected element, such as the UTM coordinate or length.

Concerning the 3D user interface for the immersed user, we use an accessible and well-known UI metaphor for system control in 3D spaces: pie menus, sometimes referred to as radial menus [26]. The touchpad on the VR controller serves as an input for the user to navigate through the menu and select the desired option on a circular list menu. The list menu is attached to the touchpad of the VR controller. Compared to graphical menus anchored in the 3D space, the radial menu does not occlude the terrain sight. There are two radial menus, one for each VR controller. One radial menu is assigned to navigation features, seen in Figure 5 and the other radial menu, to interactive features.

3.2.2 Dynamic View-point Selection

For terrain exploration and annotation, an essential feature of the prototype is navigating the environment in VR in a meaningful

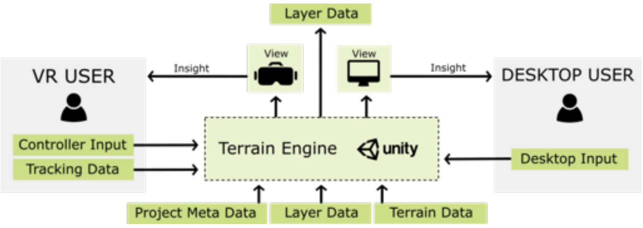

Figure 4: Data and information flow of our prototype.

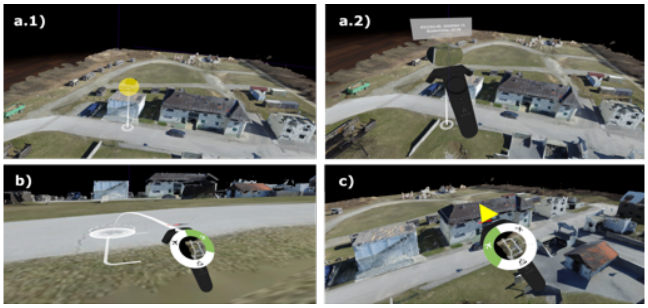

Figure 5: The prototype provides three different navigation methods for the immersed user. **a)** The table mode. Image **a.1)** shows the avatar of the user on the terrain, and image **a.2)** shows the magnified view and the metadata, such as terrain coordinates, while the user interacts with the avatar. Image **b)** presents the first-person navigation using teleportation and image **c)** 3DoF steering using the trigger.

way. The controller dedicated to locomotion commands provides the immersed user with a straightforward interface for navigation. Furthermore, the user can explore the 3D terrain from different viewpoints and adjudicate spatial structures and terrain properties. We implemented three different methods to navigate the geographical environment in VR to provide meaningful locomotion for various data types, resolutions, and travel distances: a table mode (Figure 5a.1-a.2), first-person navigation (Figure 5b), and 3DoF steering (Figure 5c). The user in VR can select the desired navigation mode on the radial menu. In the center of the radial menu, seen in Figure 5b-c, a miniature map indicates the position of the user in VR on the terrain. Above the controller, a compass offers additional guidance and is a well-known metaphor for military personnel to orient themselves in a given space. Teleportation (Figure 5b) is a well-known locomotion technique for VR, facilitates fast movement across long virtual distances, and works well on fine reconstructed terrain, like urban areas. The user in VR can inspect reconstructed buildings and structures closely. This way, the officers and commanders can include reconstructed spatial information about the local infrastructure of mission sites in their decision-making process.

3.2.3 Awareness Cues for Collaboration

The communication processes between users vary depending on the phase of the staff exercise. During planning, domain experts work together towards the group goal, and during briefing/debriefing, the domain experts communicate strategies with the commander and vice versa. An essential objective of this prototype is to enhance collaboration and support the decision-making process during mission planning.

Communication is a crucial part of efficient teamwork and includes verbal as well as non-verbal cues. One implemented cue for communication for the immersed user is the **VR-pointer**. Related work [41], as well as our own observations at the field study, showed that ray-casting supports the situational awareness of both users. During the presentation phase, the decision-maker pinpoints positions on the paper map and orders the officers to alter their strategy, investigate certain circumstances, or inquire more information about the task context. Similarly, the pointer in VR supports collaboration by providing non-verbal communication from the immersed user to the others observing the actions of the immersed user on the desktop monitor. For the same reason, we provide a **Gaze-View** on the desktop UI, which allows the desktop operator to observe the actions of the immersed user, from their viewpoint in VR, on an adjustable window in the desktop UI. Additionally, we represent the **immersed user's avatar** on the topographic map view on the 2D UI for the desktop operator. If the immersed user navigates the scene using 3DoF steering or first-person mode, the avatar's position on the map view on the desktop UI is synchronized. This way, the user on the desktop can see and analyze the current position and orientation of the immersed user on the map. We provide a **synchronized environment** for both users to simulate a common task space, similar to our observations at the field study, where groups worked physically together on a task at the same time. Changes made in the scene, such as terrain annotations or disabling/enabling annotation layers, are visible to all users, concurrently. This allows **distinct collaboration**, where user A starts a task and user B finishes the task, with the help of user A. For example, during the briefing/debriefing phase, the coarse placement of markers in VR is done by the commander and the refinement by the desktop operator. This way, two users can split a task when working collaboratively.

3.2.4 Features for Terrain Annotations

In our prototype, the virtual environment serves as a task space for tactical planning. Users add information related to their strategy, reason from others' visual instructions, and decide about future tactics. More than one user can annotate the terrain and work on a given task simultaneously. The objective of the prototype is to support officers during the planning phase by providing tools to annotate the terrain. The following features were implemented to annotate and avoid visual clutter: **annotation layers, 2D and 3D drawing, marker placement** and **terrain texture management**.

Annotation layers are abstract objects arranging annotation elements into groups. The annotation group arrangement is inspired by the transparent sheets overlaid on paper maps used by the staffs to organize different ideas. Digital solutions allow a faster switch between layers than transparent sheets and can be easily transferred to other GIS software. The idea is to group terrain annotations by task and avoid visual clutter overall. The desktop operator can create annotation layers in the layer management window on the desktop UI. Every layer is exported to a separate layer file (.csv) and can be imported to another instance of the same project, allowing for parallel or future editing.

Based on our observations at the field study, we need four main **annotation types** in the prototype to replicate current annotations drawn on a paper map: **points, lines, polygons, and markers**. The first three can be created using 2D drawing on the desktop, and 3D drawing in VR. An annotation element placed by any user is assigned to the currently active annotation layer. The primary purpose of 3D drawings is to leverage the immersive setup for terrain annotations. The officers can annotate the 3D terrain directly in VR, using the controller. The immersed user can draw a polyline by pressing the respective button on the VR controller and moving the controller simultaneously. Figure 6 shows examples of the available annotation types from the perspective of the desktop and immersed user. While annotations created by the desktop operator are automatically anchored to the terrain surface, the 3D lines created by the user in VR are placed independently in the 3D space. Figure 6a, shows the same annotations as in Figure 6b, but from the perspective of the desktop operator instead of the immersed user. Every line, area, point, and marker is accompanied by an invisible 3D mesh used for collisions.

The fourth annotation type is **markers** (Figure 1b), symbols based on the NATO standard called NATO Joint Military Symbology [36]. This standard provides symbols for military operations and units on land, air, space, or sea. Both the desktop operator and the immersed user can create markers at specific UTM locations, and delete existing ones. Additionally, the desktop operator can edit marker properties. This is a useful feature for the commander during the briefing/debriefing phase. In this phase, the commander can add a specific marker position on the terrain in VR and the marker is then completed by the desktop operator according to the instructions of the commander. In this case, the commander can leverage the ben-

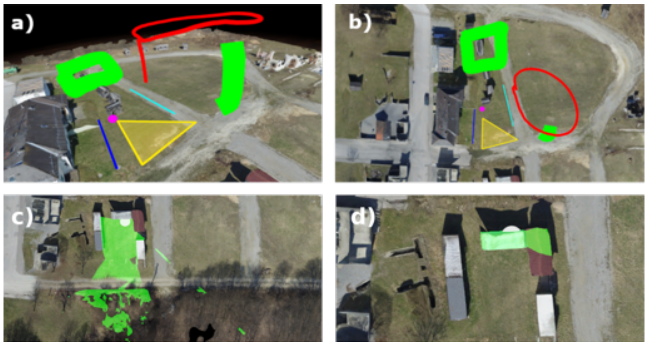

Figure 6: **a-b)** 2D and 3D annotations from the perspective of the immersed user and the desktop operator respectively. **c-d)** The visibility tool analyzes line-of-sight. **c)** The sphere is placed in the corner of a building. Visible areas are colored in a green shade. **d)** If the sphere is placed inside a building, nothing outside the building is visible.

efits of the immersed medium, the 3D perspective, while choosing the location of the element, and the desktop operator can complete the placed marker efficiently.

A common challenge of annotated data is visual clutter and information occlusion [55]. To reduce visual noise, caused by the terrain texture, we implemented **terrain texture management** for the desktop operator. The operator can disable the currently visible terrain texture to highlight other information communicated through the terrain annotations. If every imported terrain texture is disabled, we use a Material Capture (MatCap) texture, to show the structure of the terrain and keep real-time calculations minimal. MatCap shading is a method to imitate lighting without actual lighting calculations to avoid performance issues [50]. Further, the user can import other terrain textures representing different information on the terrain, for instance, aero photography, weather heat map, contour lines, or a previously annotated texture. The desktop operator can adjust the visibility of a texture by changing the alpha value on the desktop UI.

3.2.5 Features for Visibility and Quantitative Analysis

Common tasks on spatial data during the military staff exercise are distance estimation and line-of-sight visualization [23, 53]. Our immersive prototype provides an intuitive way to analyze coverage from a given viewpoint and extract quantitative measurements, such as distances or areas. We implemented the following features facilitating visibility and quantitative analysis: **line-of-sight visualization** and **query of quantitative object properties, like length and circumference, and distance measurement**.

Figure 6c-d depicts the results of the implemented **line-of-sight visualization**. The user in VR can choose an arbitrary 3D origin by adjusting the position of a white sphere. The surrounding terrain visible from that position is highlighted using a light green shade, representing the positive line of sight, as shown in Figure 1c and Figure 6. Areas without a green shade are not visible from the current position of the sphere. The desktop operator and the immersed user see the visible area from that position and can adjust their tactical strategy for the given exercise task accordingly. For this analysis, we use a custom terrain shader and a light source. The white sphere represents the origin of a point light, and the green shade is the shadow from that light source.

In addition to line-of-sight visualization, the prototype provides features for **quantitative analysis**. Both users can query properties from terrain objects, such as annotations or the terrain itself, using the pointer in VR. The immersed user can utilize the virtual ray to retrieve the geolocation of terrain points or object properties, such as the circumference and area of a region of interest or the distance between two selected points on the terrain as seen in Figure 1d.

4 QUALITATIVE FEEDBACK

In this study, we set out to investigate if the proposed VR prototype could facilitate tactical resource planning on spatial data and the overall potential of a VR-based solution for the planning process. We conducted semi-structured interviews with three military experts in geodesy and geospatial analysis. Two of the experts were part of the consultations of Section 3.1.1. The experts learned how to use the application in demonstrations held by the research and development team and a user guide that was provided. After the prototype was delivered, the experts have used the prototype themselves, showed it to different military departments, and participated in several field tests in Q2 and Q3 of 2021. Geospatial experts accompany missions and staff exercises but do not engage in the planning activities actively. They stay alert to prepare any geoanalysis product that may be requested by the exercise participants on short notice, for example, information about visibility, the slope of the terrain, quality of the subsoil, or possible bottlenecks in a pathway. The VR Tactical Resource Planning System is one of the options provided by the geospatial experts for geoanalysis during a mission or staff exercise.

We would like to note that neither the usability of the prototype nor the UI was the subject of this study. At this early phase of the prototype, we focus on the utility of the proposed features for tactical resource planning on spatial data and the practicability of VR solutions for this use case.

4.1 Study Design

The interviews, each 30 - 40 minutes, were conducted one by one online via teleconference call. We prepared an interview guide with core topics to be discussed: their experiences with the VR prototype in the field, their professional opinion about the VR prototype, and their general opinion on VR-based solutions to support the participants in a staff exercise. We evaluated the data through a thematic analysis of the transcriptions, by identifying and analyzing patterns to optimally derive design implications and judge the potential of VR tactical resource planning. Our results are based exclusively on the content of those one-time interviews and on no other communication held with the experts during the research period.

4.2 Interview Evaluation

This section presents the results of our thematic analysis and summarizes the main topics extracted from the transcripts.

4.2.1 Geoproducts

All interviewees confirmed that paper maps are the standard tool used by the officers in a staff exercise. According to the experts, the standard map used in a regular training session in the military schools has a map scale of 1:50000. *"The problem revolves around this very specific map. When they request a geoproduct for the exercise, it is usually this map. In some cases, we offer different geoproducts that could improve the understanding of their problem space. Effective communication is key to understand what the commanders and officers need.- P02"*. Even though paper maps are commonly used, the interpretation of the 3D topology from the 2D map requires specialized knowledge. A solid 3D impression of the mission site is crucial because they require less mental load to understand. *"The problem with a paper map is that you have to be able to read it and imagine what the terrain looks like. [...] The third dimension is a useful additional piece of information to understand the terrain. - P01"*. The fact that 3D terrain can be understood more easily was acknowledged: *"You don't have to create a mental model of the map anymore, but focus on critical areas. [...] In the best-case scenario, they should be able to grasp the terrain intuitively and then concentrate on the task at hand. - P02"* .

4.2.2 Impression of VR-based Tactical Resource Planning

VR provides an immersive experience, where the 3D representation of objects, terrain, and spatial data, in general, can avoid scale interpretation errors. This was pointed out as one of the most prominent characteristics of VR to facilitate the understanding of 3D structures. *"In VR you have a 1:1 representation. If there is a command post flag, it's true scale, so you get what you see. On a paper map, depending on the map scale, it looks different, objects can be 10m or 100m away from other point-of-interests. - P01"*. Further, VR can help users to work on the map without distractions: *"If I see nothing but the terrain, I am mentally present in the scene. There is no distracting background noise, I can concentrate on the scene and get to know the terrain more intensively. [...] This is more accurate than looking at photos, or on a display, or on a map. - P02"* .

The drawbacks of the system were discussed too: *"You can't present the terrain to many people in VR, and I can't take the VR setup out into the battlefield. Paper maps are very mobile and produced in large quantities. Out there, the VR setup is rather useless because the devices can die. - P01"*. The benefits are subtle if the imported terrain has a flat topology: *"If the mission site consists of a relatively flat area or flat data, the positive effect may not be noticeable in VR anymore. - P02"*.

Some statements from the experts implied that the acceptance of VR tactical resource planning tools is dependent on user attitude and age: *"Different generations participate in the staff exercise. Older participants can do their tasks efficiently on a map and use it too. We also have the very young ones who want to learn through play. They put themselves in VR and eagerly ask what the application is capable of. The older people usually send the young ones into VR and command them to look at something and to report back to them. - P01"*. Participant's tech-savviness influenced their motivation as well: *"You notice who is tech-savvy and who is not. You can judge whether someone is an experienced computer gamer and who is not. [...] Non-gamers are usually only in VR for 10 minutes and never again. - P03"*. Also: *"For now, the VR application is a complementary tool, they don't have to use it. It depends on how technology-savvy the staff members or participants are and whether they want to adapt. - P02"*. Another mentioned factor for acceptance was interoperability. In particular, the seamless integration of VR into current processes and other tools used by geodesy experts and staff exercise participants, for instance, their custom command and control software for military operations. *"I would like to see more automation and work less with other programs. - P01"* and *"The prototype can be helpful for now, but it must be interoperable with our other software [...] We want to create an information flow between the web tools, the VR tool, the command, and control system, and GIS. The data formats and content should be transferred from one software to the other without friction. No single solution, otherwise it's just a nice presentation but serves no purpose. - P02"*.

Further, the interviewees agreed that the VR application should be integrated into the education of new officers to potentially increase the acceptance and understanding of the technology. *"VR is not part of the training. [...] I know we can use the application purposefully, but the officers don't know how to use it, if you are not taught, how are you supposed to know? [...] Generally, VR should be integrated as closely as possible into the current processes that already exist. - P03"*. According to the experts, the current prototype is not optimally integrated into their current operations. Nevertheless, they are convinced of its potential: *"They learn how to solve a problem without VR. They can solve the tasks with the maps. Currently, VR would only add time and in a staff exercise, time is scarce. If VR is accepted as a standard tool in the training of staff members and officers, then we have reached our goal. That's the challenge, that VR is not seen as a time-consuming extra tool, but as a valuable addition that achieves their objectives more economically. - P02"*. From the perspective of the geodesy experts, VR is not a tool but used as a medium to present their work. In summary: *"VR is a frame in which geoinformation products can be presented. [...] The VR prototype is an additional medium where we can present results. [...] Several different terrain analysis results can be visualized at the same time, and then we might derive a connection useful for the understanding of the operational area. - P02"*.

4.2.3 The Prototype

The interviewees talked about the features provided by our prototype and gave suggestions for improvements. An expert mentioned an interesting situation observed during a staff exercise: *"The task was to close off an area, so no one can get in nor out. The officers had to place railroad embankments effectively to do so. One staff group thought that their solution, done on a paper map was good. Then, they got into VR, explored the area, and realized that their railroad embankments in their current solution are not close enough because hostile groups still had a line of sight to the target. So they placed their barricades 2 or 3 streets closer. Another group didn't use VR, only paper maps, and lost the task because they were exposed to the fictitious enemy. [...] You could see very well that VR can be beneficial. - P01"* Also, the terrain measurement tool was positively brought up: *"It comes down to the question of trafficability. For example, do our vehicles fit the dimension of a bridge? If you drive a tank, is the bridge too narrow? - P02"*. Regarding the texture layer management, P01 stated: *"It is useful to switch between the individual texture layers. (..) we used two textures showcasing the explosion of the 2020 Beirut harbor, how the surrounding area looked before, and how it looked one day after the explosion [...] This feature has a lot of value because you can show the commander, who is using VR, the essence of the analysis. - P01"*.

Though the experts stressed that the 3D drawing is useful, they referred to possible improvements to increase the usability of our prototype. For instance, the drawing tools should resemble the act of drawing on paper maps. *"3D drawing directly on the terrain surface would be very important. Regarding the desktop operator: If the operator draws, there is a gap between the drawing and the terrain surface. Drawing either on the ground or at a certain height would be more practical. - P01"* and *"It takes practice to draw in the air. [...] it would be better if we could draw directly on the 3D terrain. - P02"*. One interviewee even suggested a different setup for efficient terrain annotation: *"The officers want to be able to draw something on a map, quickly. [...] It would be nice to draw with our hands on a handheld device and then the information is transferred onto the terrain in VR. [...] The officers draw a lot on paper maps and many like to do that. [...] There is also a difference between a computer mouse and a pen. The pen is more comfortable and faster. - P03"*. Concerning the immersive line-of-sight analysis, one expert described an experience they had at a staff exercise: *"One staff wanted to do a line-of-sight analysis in VR, but it did not work out. Weather conditions, such as smog or wind can affect visibility. This is not included in the current prototype. - P03"*.

At the end of every interview, we talked about their opinion on how we can improve the current VR prototype. One noteworthy statement concerned user collaboration: *"Imagine the commander is in VR and wants a custom geoanalysis. In an optimal situation, the desktop operator works on this request without the commander to see, so the commander can work on other tasks. As soon as the analyst is done, the newly created annotation layer showing this analysis is unlocked and visible for the commander. Currently, the visibility of scene objects is in sync between VR and the desktop operator. However, asynchronous is also desired. I would like to be able to disable layers for the commander in VR, but still visible to the desktop operator. - P01"*.

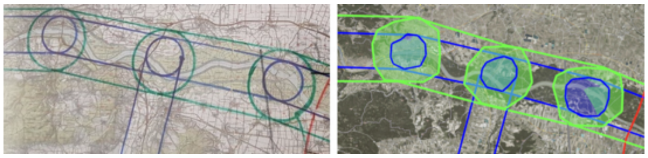

Figure 7: An example of a tactical strategy. **Left:** Drawn on a transparent sheet and overlaid on a paper map. **Right:** The same strategy realized using our prototype.

5 RESULTS

We use the results of the thematic analysis of our interviews to answer our research questions, starting with Q1: *What potential lies in VR-based tactical resource planning using spatial data?*

The overall attitude of the interviewed experts towards VR-based planning was positive and reinforced our assumption, that immersive viewpoints on spatial data are beneficial to understand geometric structures, which is in line with findings of existing related work [6, 24, 27, 48]. Based on their observations, officers and commanders were able to place annotations in the immersive environment more accurately and work in an environment with fewer distractions.

The interviews showed us that the potential of VR-based tactical resource planning in a military staff exercise depends on the following aspects:

- **User attitude and experience:** Tech-savvy people are more easily motivated to use the new technology.
- **Usability and interoperability:** Efficient design and seamless integration into current processes and software tools of a staff exercise are vital. Those two aspects are even more crucial if the task in VR has to be executed as fast as possible.
- **Early adoption:** Our experts emphasized that introducing new technology into traditional processes is complex and people might be more eager to use VR hardware if integrated into the curriculum as early as possible.

Nonetheless, in the context of a military staff exercise, there are several challenges for the proper adoption of VR hardware. According to our interview partners, digital mediums, such as VR, can not be reliably used beyond the safe environment of a staff exercise. On mission sites, environmental conditions, such as temperature, lack of electricity or small spaces influence the practicability of VR hardware. Evidently, under such circumstances, they have to roll back to paper maps. These insights are similar to previous research investigating the role of VR in military training [33].

To answer Q2: *How can we design VR applications to facilitate efficient tactical resource planning on spatial data?*, we use our qualitative feedback on the prototype to derive general design considerations for VR tactical resource planning tools.

The interviewees positively reinforced the available scope of operations for our derived use cases, terrain annotation (see example in Figure 7), visibility, and quantitative analysis, for tactical resource planning in VR. The 3D drawing feature, immersive line-of-sight analysis, and first-person navigation were highlighted as useful, though there is room for improvement regarding usability. Two interview partners mentioned insightful experiences in the field, proving that VR can have significant advantages over paper maps: the barricade correction in VR, and the measurement of narrow roads and bridges for vehicle selection. Additionally, in comparison to 3D maps visualization, VR provides an additional way to apprehend information in true scale. One expert mentioned the missing weather conditions for visibility analysis, which could be an impactful extension in future work.

From the interviews, we derive four design implications for the seamless integration of VR-based tools in the current tactical resource planning process for missions and staff exercises.

1. Our results support our assumption that terrain annotations and quantitative analysis are essential for tactical resource planning tasks on spatial data, similar to previous work [17, 53].
2. In some cases the feature design and UI in VR should match traditional workflows (e.g. as direct 3D drawing on the spatial data) to decrease the learning curve.
3. The collaboration type and teamwork of traditional planning processes influence the collaboration in virtual environments. Due to the rapid decision-making required for tactical resource planning, a synchronized work environment for all users is not advantageous for every planning task and the possibility of asynchronous collaboration should be considered.
4. With the current technology of VR HMDs, VR-based tactical resource planning tools should not aim to take over the entire planning process but should be customized to solve sub-tasks of the entire process where it is the most advantageous in comparison to existent available alternatives.

6 CONCLUSION AND FUTURE WORK

In this paper, we presented the feature design, implementation, and preliminary evaluation of a VR-based tactical resource planning application. We described our findings from observations at an on-site military staff exercise and the derived feature requirements for VR-based planning tools. Further, we explained our technical setup and the motivation behind our design and development. To evaluate our VR prototype and investigate the potential of VR-based tactical planning in military staff exercises, we conducted semi-structured interviews with three military geodesy experts that accompanied field tests of our prototype.

Our results confirm previously known benefits of immersive environments, also for the presented use case. Analysis of the topology of geographical data in VR can lead to a broader and more intuitive understanding of the terrain. We presented the design of our VR prototype and key insights derived from our expert interviews to provide design implications helpful for future endeavors designing immersive spaces for tactical resource planning for military staff exercises or related settings, such as space missions or disaster prevention. Our evaluation showed that the potential of VR-based planning solutions in a staff exercise depends on environmental factors, such as the tech-savviness of the participants, the participant's general attitude towards technology, interoperability of the system, or the previous experience of the users.

While domain experts can judge the potential of our approach based on their experience, background knowledge, and observations, we are aware that their opinion might not fully reflect the user experience of end-users. Due to the Covid-19 pandemic, we were not able to conduct the planned large-scale user study to assess the usability and effectiveness of user interactions. In future work, we want to improve the interoperability of our VR system with other software used by geodesy experts and staff exercise participants to allow an uninterrupted working process and include a quantitative and qualitative usability study with standardized questionnaires and quantitative metrics to understand the bottlenecks and merits of our 3D interaction design.

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