Utility of 3D eXtended Reality for Terrain Understanding

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ABSTRACT

In military operations, there is growing interest in using eXtended Reality (XR) technology to visualize and interact with 3D virtual mission areas for planning and rehearsals. One key advantage of XR technology is its ability to visualize areas of operation with perspective views and depth perception, allowing users to explore terrain models more naturally. A pilot user study has been carried out to compare the use of immersive XR technology for two types of terrain analysis tasks. The focus was to observe how XR supported features such as motion parallax and depth cues impact task performance measures such as speed, accuracy, confidence and perceived workload. Additionally, we interviewed participants with prior military training regarding the applicability of the immersive terrain exploration tool. Our findings indicated that the XR tool engages participants with higher immersion and sense of presence in the terrain, combined with the user interface features, supported a quicker and more accurate as well as confident responses in the terrain tasks related to assessing elevation and line of sight. The interviews resulted in insights regarding XR tooling features that would better support terrain analysis tasks involved in land-based operations, such as incorporating a compass within the immersive environment, visualizing line-of-sight data, delineate terrain and surface types (i.e. rocks, swamps, forests), and displaying scale. These findings suggest that integrating XR technology into military education and training programs can significantly enhance terrain analysis proficiency by providing immersive, intuitive environments that improve spatial understanding, task accuracy, and user confidence. The heightened sense of presence and interactivity allows trainees to engage more deeply with virtual mission areas, potentially accelerating learning and retention. Furthermore, the participant insights point to valuable design considerations that can make XR tools more effective for instructional use in preparing personnel for complex land-based operations.

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INTRODUCTION

Immersive extended reality (XR) systems enable the rendering of and interaction with three-dimensional (3D) virtual mission areas, allowing users to explore complex environments in a more intuitive and embodied manner. Compared to traditional two-dimensional (2D) map representations, XR offers enhanced perceptual realism, more effectively conveying spatial features such as depth cues, distance recognition, and occlusions. These immersive systems support a range of interactive functionalities including zooming and panning, dynamic perspective switching (from top-down to first-person view), and locomotion through the virtual terrain. XR-supported interactive features support motion parallax, stereopsis, and structure-from motion as additional depth cues. Such interactions improve the visibility and interpretability of local features, including subtle elevation changes, occlusions, and line-of-sight considerations, which might otherwise be overlooked in flat map views. Traditionally, mission planners are required to mentally reconstruct a three-dimensional understanding of terrain from 2D maps—a cognitively demanding process that depends on spatial reasoning and cartographic expertise. XR has the potential to alleviate this cognitive load by providing direct spatial context through immersive visualization and interaction.

The scope of this study is a user-focused investigation to explore terrain visualization and interaction and its role in optimizing training outcomes. The utility of XR-based virtual mission area supports spatial interactions that positively influence terrain comprehension. The objective of this paper is to address what types of interactions users engage in when navigating 3D terrain environments and how these interactions support core analytical tasks. The purpose is to identify where XR technologies can provide added value, can better support which terrain tasks, and can inform future applications in terrain analysis education and training.

Prior research has explored the relative strengths and limitations of two-dimensional (2D) and three-dimensional (3D) visualizations in terrain analysis tasks. Findings consistently suggest that 3D visualizations enhance comprehension of terrain shape and structure, particularly for non-specialist users. Popelka and Brychtová (2013) reported that 3D displays improve terrain understanding for users without formal cartographic training. Similarly, John et al. (2000) found that 3D representations were superior for shape understanding and topographic interpretation, while 2D maps performed better for assessing relative positions and precise elevations. Merritt et al. (1997) demonstrated that 3D visualizations significantly improved task performance in identifying terrain features such as elevation and line of sight. These findings were further supported by Li et al. (2017), who showed that 3D models aided in interpreting complex terrain topography. Lester et al. (2020) also pointed to improved slope perception in immersive 3D environments, which is critical for tasks such as route planning.

However, the advantages of 3D are not uniform across all task types or user groups. Savage et al. (2004) found that 2D representations were more effective for focused tasks unrelated to elevation, and did not observe a consistent benefit of 3D for other task categories. In a study by Wagner et al. (2023), VR users performed better when tasked with finding routes of minimal gradient, but required more time to complete the task—highlighting a trade-off between accuracy and efficiency. Wood et al. (2007) similarly noted that 3D visualizations improved terrain shape comprehension, whereas 2D maps supported more precise localization tasks. Furthermore, user expertise appears to moderate these effects. Bennett et al. (2014) observed that non-specialist users performed better with immersive 3D environments, while domain experts preferred 2D geographic information systems for tasks involving detailed or analytical spatial interpretation.

Collectively, these studies underscore the complementary roles of 2D and 3D tools in terrain analysis. While 3D visualizations support more intuitive spatial understanding and user engagement, especially for novices, 2D tools remain effective and efficient for certain analytical tasks, particularly those requiring precise measurement or positional accuracy. These studies did not investigate the impact and effectiveness of user interactions with and embodiment within the virtual terrain.

The current study explored how military reservists with varying training backgrounds interact with our immersive XR-based virtual mission map, and how their use of this tooling compares to a more traditional method—a physical 2D map—when completing two types of terrain analysis tasks. We present initial findings from an early evaluation of our XR-supported terrain exploration system. This pilot study serves as a preliminary test of the tool's usability and value, focusing on collecting qualitative feedback rather than producing statistically significant results. A small sample size was intentionally used to gather general impressions and assess whether further development is warranted. The main goal of this work is to understand how perceptual features supported by XR, such as motion parallax and depth cues, impact task performance metrics such as speed, accuracy, confidence, and perceived workload. Our expectation is that these immersive elements will enhance user performance, increase confidence, and support deeper engagement during the tasks.

By comparing participant behavior and outcomes across both the XR and traditional map conditions, this study aims to provide empirical and observational insights into why XR tools should be integrated into military terrain analysis training and mission planning workflows. In a future study, we would like to investigate how and where XR tools could be integrated in the training and education curriculum.

Research Question

Does a 3D virtual mission area presented in an immersive XR environment enhance terrain analysis task performance and reduce perceived workload compared to traditional 2D maps? What specific user interactions within the XR environment add value to terrain understanding?

The rationale is that 2D map analysis relies on abstraction and cognitive reconstruction of depth, which places demands on working memory and spatial reasoning. In contrast, 3D immersive environments directly engage multiple depth cues—such as motion parallax and stereopsis—reducing the need for mental reconstruction and enabling more intuitive perception of terrain structure.

We hypothesize that the XR system will lead to improved task performance, higher confidence in responses, and lower perceived workload compared to 2D maps.

METHOD

To address the research question, we conducted a pilot study comparing two visualization methods: a traditional 2D physical map and an immersive 3D XR map. Participants completed two terrain analysis tasks, i.e. elevation and line-of-sight, using both map types. The same geographical area was used across all trials to ensure consistency between conditions.

Approach

We developed an immersive virtual environment featuring a high-fidelity 16 km by 16 km mission area in northern Norway. This environment was created using a 0.5-meter resolution satellite image (from commercial sources) and a 1-meter resolution elevation model (sourced from Norwegian open data). Vegetation was analyzed through the ARA architecture (Kuijper & Smelik, 2022), resulting in geo-specific representations of individual trees with accurate height data. Buildings were imported from existing vector datasets and enriched with elevation-based height attributes. Road networks were derived from OpenStreetMap, and water bodies were integrated using publicly available vector data from the Norwegian Water Resources.

Our XR solution provides a fully immersive 3D visualization of this virtual mission area. Using a head-mounted display (HMD), users experience motion parallax and stereoscopic depth cues, with each eye receiving a slightly different image for enhanced spatial perception. The HMD's head- and hand-tracking capabilities allow users to physically navigate and interact with the terrain model—walking around the map or manipulating it with natural hand gestures to pan, zoom, and rotate. These embodied interactions generate motion parallax, a key depth cue absent in static 2D maps (Sweet & Kaiser, 2011). Figure 1 shows a screenshot of the 3D virtual mission area displayed on a blue tabletop.

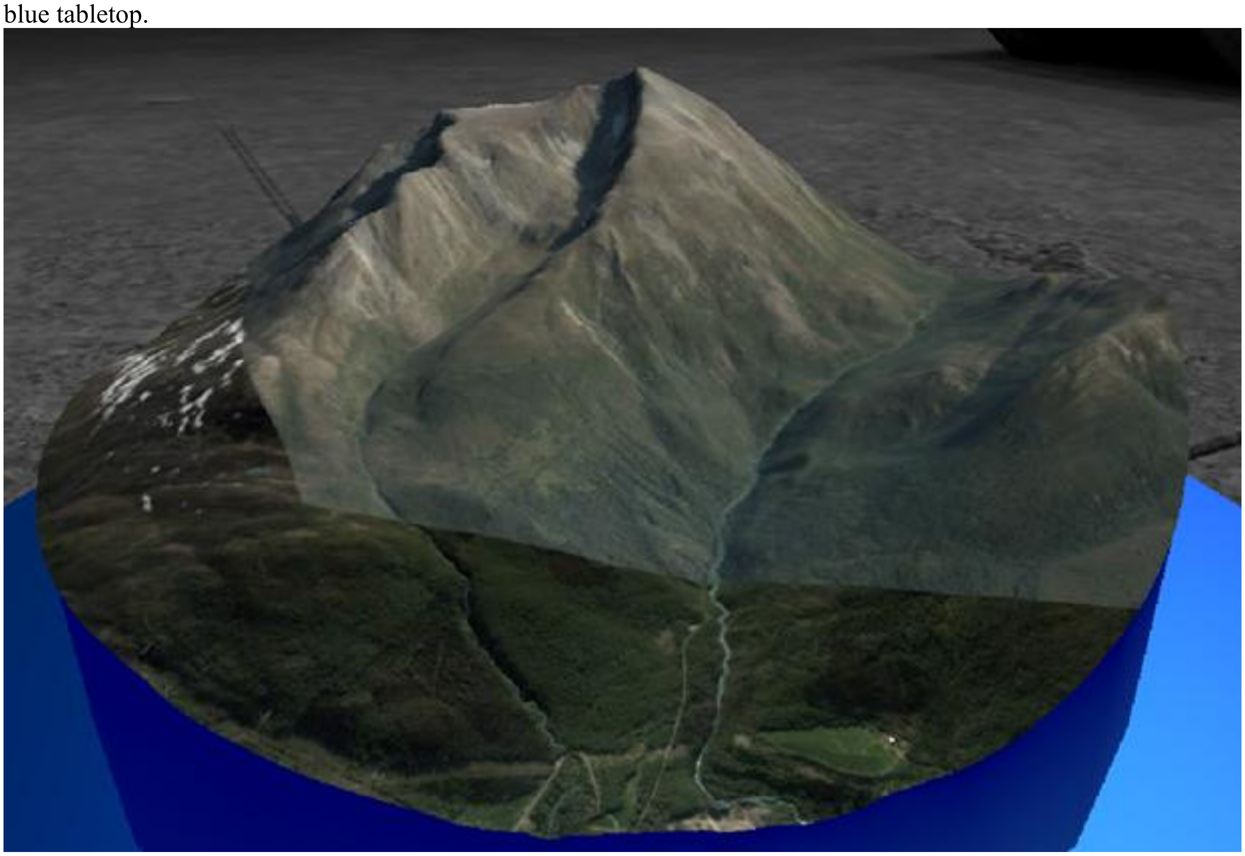

Figure 1 Example of the 3D map in our XR Solution. A region of the 16km x 16km 3D map is displayed on a virtual tabletop that is placed inside a virtual room. Users can interact with this map by rotating, panning, zooming, switching perspective, and adjust the height of this map. The map is also viewable from all angles, so users are encouraged to physical walk around the map to get different viewing perspectives.

To further support user interaction, we implemented additional UI features in the XR solution, including dynamic panning, rotation, zooming, perspective switching between top-down and first-person views, and adjustable terrain height within the physical space.

Experiment Design

Four participants took part in the study. The small sample consisted of army reservists with prior land navigation training and was intended to provide early insights into the XR tool's utility. All participants had received formal military instruction in map reading and route planning, though none had extensive operational experience. Their familiarity with virtual reality was minimal, ranging from none to very limited use of XR headsets.

Each participant completed seven trials per condition. In each trial, a unique set of three markers (labeled A, B, and C) was placed on the map. In some trials, an additional red marker indicated an enemy position. These trials were conducted using both the 2D physical map (Figure 2) and the 3D interactive XR map (Figure 3).

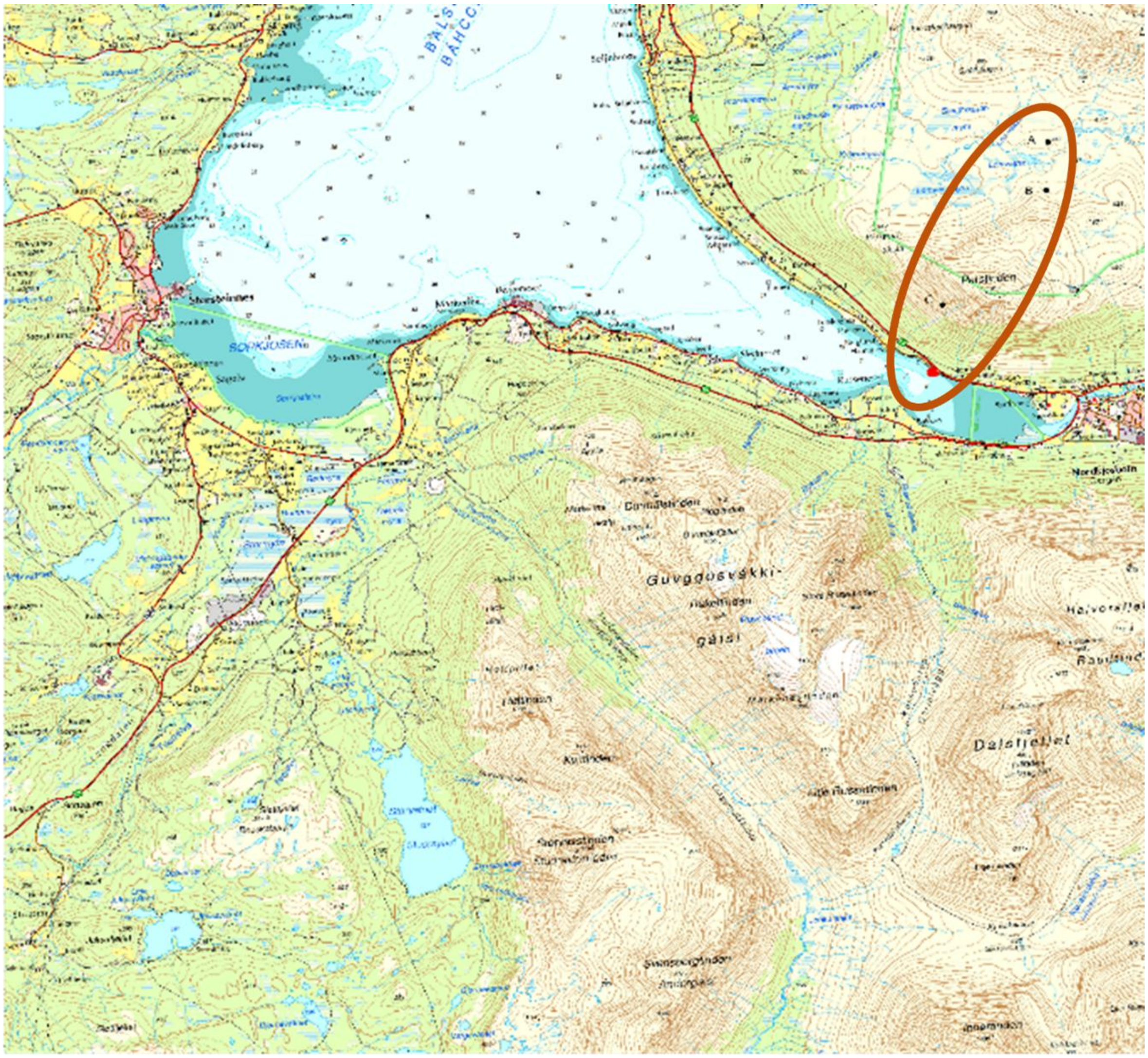

Figure 2 Example of 2D map with markers for line-of-sight identification task. The participants are tasked to first identify the highest elevation out of marker locations A, B, and C (highlighted here for illustration purposes). Then, participants are asked to assess whether the locations could be seen from the red dot denoting the enemy position. We refer to this task as "line-of-sight" identification.

Figure 3 Example of a line-of-sight identification trial in XR. The 3D interactive map has location markers A, B, and C, and an enemy position represented by the red dot and labeled target. The location markers are placed at the surface level, but their labels (as seen in this figure) are floating at a height that is visible from all viewing angles. Participants may utilize the UI features in this XR tool to make a response.

Terrain Tasks

In each trial, participants completed one or two tasks using the location markers on the map.

Task 1: Highest Elevation

The first task ("**Task 1**: highest elevation") involved identifying which of the three markers (A, B, or C) was located at the highest elevation. In the 2D map condition, participants had to interpret contour lines to estimate elevation levels (Figure 4 illustrates these elevation lines).

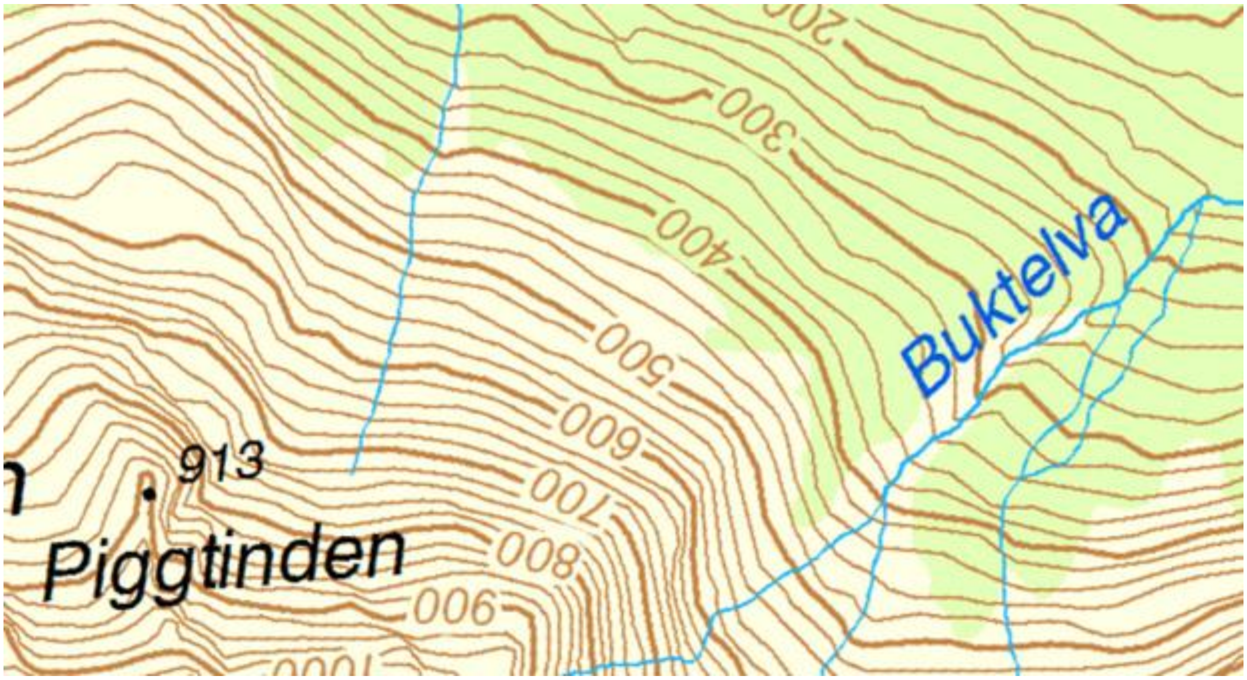

Figure 4 Elevation lines on a 2D map enlarged and replicated here for illustration purpose. In this example, there are no location markers from a given trial.

In the 3D interactive XR map condition, elevation lines were not present. Participants could rotate the map or physically move around it to view the terrain from different angles, allowing for more intuitive assessment of elevation based on visual depth cues.

Task 2: Line-Of-Sight (LOS)
The second task ("**Task 2**: LOS") required participants to determine which of the three markers (A, B, or C) were visible from the enemy's location, indicated by a red marker. This line-of-sight task was more complex, as it required understanding both relative elevation and terrain-based visual obstructions (e.g., hills, ridges, or dense vegetation). Participants needed to assess whether any terrain features would block the enemy's view of each of the three locations. Because the line-of-sight task was more cognitively demanding, requiring spatial reasoning and interpretation of terrain features, it was included in more trials than the elevation task.

The study design did not use counterbalancing; all participants completed the 2D map condition first, followed by the 3D XR condition. This introduces a potential order effect, where participants might become more familiar with the task format over time. However, to mitigate simple memorization effects, the marker locations varied across trials, preventing participants from recalling specific answers.

Experimental Measures

Response Times
Response time was measured in seconds using a stopwatch, capturing how long each participant took to complete the task and formulate an answer for each trial. Participants were informed that they were going to be timed on completing each task.

Confidence
Participants rated their confidence on a self-reported scale from 0% to 100%, with 0% indicating complete uncertainty and 100% indicating complete certainty in their response.

Mental Effort
Mental effort was assessed using the unidimensional Rating Scale for Mental Effort (RSME), ranging from 0 (no effort) to 150, with 115 representing extreme effort (Zijlstra, 1993).

Task Performance
Because the experimenters lacked formal training in map interpretation, it was not feasible to determine ground truth answers. Instead, we used inter-rater reliability as a proxy for task performance. The assumption was that easier, more intuitive tasks would lead to greater agreement among participants, while more complex or ambiguous tasks would result in lower agreement.

Inter-rater reliability was calculated using Fleiss' Kappa for multiple raters. The resulting K-values were interpreted using the classification guidelines from Landis & Koch (1977), as shown in Table 1. Reliability scores were determined through visual inspection across all trials combined.

Table 1. Inter-rater reliability scores

Kappa Value	Level of agreement
0	Poor
≤ .2	Slight
≤ .4	Fair
≤ .6	Moderate
≤ .8	Substantial
≤ 1.0	Almost perfect

Workload
Workload was measured once after the completion of each condition using the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988). The weighting of the scale items was determined by the experimenters.

Usability Ratings
Usability was assessed after each condition using the Virtual Reality System Usability Questionnaire (VRSUQ) (Kim & Rhiu, 2024).

Qualitative Feedback via Post-Experiment Interview
Upon completing all trials, participants took part in a semi-structured interview. This allowed them to share open-ended feedback on the tool's features, perceived usability, and overall experience.

Procedure

Upon arrival, participants were briefed on the purpose and structure of the evaluation. They were shown a PowerPoint presentation containing sample images of the two map types and received instructions on how to perform the two tasks.

All participants began with the 2D map condition. This choice allowed task instructions and questionnaires to be presented on paper, giving participants the opportunity to review and familiarize themselves with the procedure before transitioning to XR. In the XR condition, task instructions were repeated verbally but not displayed in the virtual environment. While this fixed order may introduce a potential order effect, we believe its impact is minimal due to variation in task content across trials. Still, future studies should counterbalance conditions to control for this possibility.

Before beginning the first official trial, each participant completed two practice trials within each condition to become familiar with the task format and interface. In the XR condition, this also allowed participants to acclimate to the controls and environment.

In the 2D map condition, paper maps were stacked face-down. Once the participant was ready, they flipped over a map to begin the trial, and the stopwatch was started. Participants indicated they had reached a decision by flipping the page back over; at that point, the stopwatch was stopped, and their answer was stated aloud. If participants responded before flipping the map back over, timing stopped at the start of their verbal response. After each trial, participants completed the relevant questionnaires before proceeding to the next one. Upon completing all trials for this condition, they filled out the NASA-TLX.

In the XR condition, participants first received guidance on using the headset and controllers. They had time to explore the virtual environment, with the terrain map (without markers) visible, and were instructed on how to rotate, move, and zoom the map using the controllers. When ready to begin a trial, they signaled to the experimenter verbally. At that moment, the markers appeared, and the stopwatch started. When participants indicated they were ready to answer, the markers were removed, and timing was stopped. After completing all trials, participants filled out the NASA-TLX and the VRSUQ.

RESULTS

For **Task 1**, where participants identified the highest elevation out of location markers A, B or C, the response times for both visualization modalities are shown in Table 2. A 14-second average reduction in task completion time was observed with the 3D map compared to 2D map when identifying the highest elevation. For **Task 2**, where participants assessed LOS and identified location(s) that can be seen from enemy position, participants were on average 21 seconds faster using the 3D map.

Table 2. Response time

Task Type	Map Type	N (trials)	Min (s)	Max (s)	Mean (s)	Std. Dev.
Elevation	2D	8	6	60	27.75	17.73
	3D	8	4	42	13.75	12.30
LOS	2D	20	12	105	39.70	28.96
	3D	19	4	34	18.63	8.57

Participants consistently completed tasks faster in the immersive 3D condition. This suggests that XR tools can improve operational efficiency in time-sensitive training environments. Faster LOS identification in complex terrain assessments further reinforce the potential of XR tools for rapid tactical evaluations in training environments.

Table 3 shows the average confidence ratings for identifying the highest elevation and LOS. A difference of more than 20 percentage points, on average, showed that participants felt more confident about their responses to either tasks in the 3D condition.

Table 3. Confidence ratings

Task Type	Map Type	N (trials)	Min (%)	Max (%)	Mean (%)	Std. Dev.
Elevation	2D	8	60	95	78.13	10.33
	3D	8	90	100	98.50	3.46
LOS	2D	20	30	100	61.00	18.04
	3D	19	20	100	82.37	20.03

The immersive 3D environment substantially boosted participant confidence, which is critical for decision-making under pressure in training scenarios. Confidence improvements indicate better terrain understanding with 3D tools—essential for training Soldiers to make accurate field judgments.

Table 4 presents rating scale mental effort (RSME) scores, a self-reported unidimensional mental effort scale. The averaged scores show that participants reported less mental effort used in the 3D condition to either task types.

Table 4. RSME scores

Task Type	Map Type	N (trials)	Min	Max	Mean	Std. Dev.
Elevation	2D	8	30	63	47.88	12.44
	3D	8	5	28	16.63	8.00
LOS	2D	20	30	80	58.00	14.73
	3D	19	10	60	27.89	17.51

Lower cognitive load in the 3D condition implies that XR may reduce mental strain, freeing up cognitive resources for higher-order analysis during training. The reduced cognitive demand in the immersive 3D condition suggests XR systems may enhance focus and retention during demanding training exercises.

Post-Experiment Measures

Task Performance
Using Fleiss' Kappa, inter-rater reliability was significantly higher in the 3D condition (K = .769, Substantial agreement) compared to the 2D map (K = .241, Fair agreement), with non-overlapping confidence intervals.

Higher agreement in the 3D condition suggests the immersive tool supports clearer and more consistent spatial understanding—an important metric for training effectiveness.

Workload NASA-TLX
The 2D map condition yielded a higher workload (M = 47.1, SD = 9.8) than the 3D condition (M = 27.8, SD = 2.8). Lower perceived workload indicates that trainees may sustain performance longer and under greater pressure when using immersive XR systems. Figure 5 shows the resulting data scored on a scale of 0 to 100.

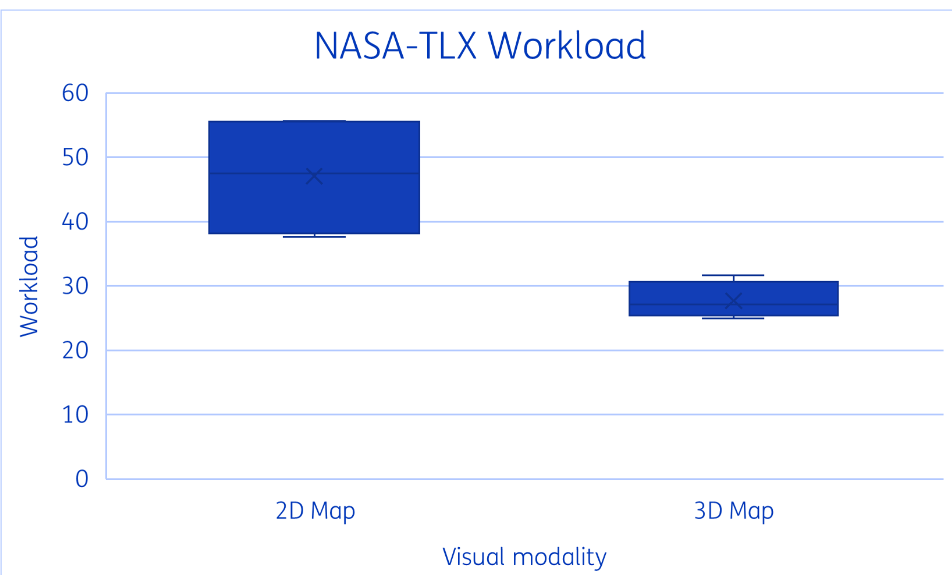

Figure 5 NASA-TLX scores show higher workload for the 2D condition.

Usability of the XR Tool
The VRSUQ questionnaire (Kim & Rhiu, 2024) was administered after the XR condition, which revealed an appraisal of the 3D condition in terms of usability. On a scale of 0 to 100 the scores were M=89.6, SD=4.2, with a range between 86.1 and 94.4. High usability scores suggest that even participants with minimal prior XR experience

could operate and benefit from the immersive system, lowering the barrier for adoption in military training programs.

Post-Experiment Interview

During the post-experiment interview participants had the opportunity to voice their opinion about the 3D XR visualization technique, in comparison to the conventional 2D maps. Out of all the remarks, a number of themes were distilled which will be discussed in order.

Map & Terrain Understanding

It is of critical importance that the user gets a good understanding of the terrain and the terrain features to be able to conduct any sort of mission planning. Participants consistently favored the 3D XR map over the 2D map, citing ease of terrain interpretation, more natural interaction, and enhanced situational awareness. Key suggestions for improvement included adding navigational aids (e.g., compass, distance scale), surface-type cues, and better line-of-sight tools. Participant feedback affirms that immersive XR tools not only enhance performance but are perceived as intuitive and mission-relevant by trained users—strengthening their case for inclusion in modern military education and training pipelines.

Terrain types

Participants generally preferred the 2D map for identifying and understanding terrain types. This preference stemmed from the 2D map's use of abstract color-coding to clearly delineate features such as water bodies, forests, and plains—information that was less accessible in the satellite-based 3D map. Additionally, the 2D maps included details such as water depth, which were missing in the 3D environment.

Key insight: While immersive, the 3D map lacked abstraction layers critical for environmental analysis, suggesting a need for customizable visual overlays (e.g., topographic, hydrological) to enhance terrain interpretation.

Elevation

Although the 2D map included contour lines at regular altitude intervals, participants overwhelmingly favored the 3D map for assessing elevation. They described the 3D representation as more intuitive, allowing for an immediate spatial understanding of height differences without the need to mentally translate contour lines into three-dimensional shapes. The contour lines in the 2D maps were described as cognitively demanding and difficult to interpret.

Key insight: Direct visual affordances in 3D maps may offer significant cognitive relief over symbolic notations like contour lines, particularly for users without advanced map-reading skills.

Usability Features for Improving XR Tool User-Friendliness

The ability to manipulate the 3D map by rotating, panning, and zooming was seen as a significant advantage. Participants found these interactive features improved their speed and depth of terrain comprehension. Despite none of the participants having prior XR experience, all were able to operate the interface effectively following a brief training session.

Observers noted that participants began to engage in natural exploratory behaviors during the XR trials. These included walking around the virtual map and physically adjusting its orientation. When answering line-of-sight questions, participants often rotated the map until the target marker was at eye level, effectively adopting a first-person viewpoint to evaluate visibility—an approach not possible with static 2D maps.

Key insight: Embodied exploration in XR led to more immersive spatial reasoning strategies, which may foster deeper situational awareness and engagement in training contexts.

Suggested Usability Improvements

Participants provided several concrete suggestions for improving the XR tooling user interface:

- Reset Function: A quick reset option for zoom level and orientation would help users recalibrate the map during use.
- Compass Integration: The lack of a compass made orientation challenging, especially after multiple rotations.

- Scale Indicator: A visible scale is needed to maintain a sense of distance, particularly when zooming in and out.
- Annotation Tools: For future use in route planning or collaborative mission tasks, users emphasized the importance of being able to annotate the map with symbols, routes, or notes.

Key insight: While the core XR system was praised for its usability, small additions—orientation aids, scale visibility, and annotation tools—could greatly enhance operational relevance and task utility.

Operational Relevance of the XR System
Participants reflected on how this XR system might be used in real mission planning or field scenarios. One major advantage cited was its usability in any lighting condition, including at night—an inherent limitation of traditional paper maps. Participants also speculated that XR equipment could be built to be more rugged and weather-resistant than paper maps, which degrade rapidly in rain.

An unexpected benefit noted was the increase in focus while using the XR system. The immersive environment helped participants feel more cognitively engaged and less distracted by their surroundings, which could be beneficial for planning in high-pressure environments—though this was acknowledged as potentially mission-dependent.

Key insight: The XR-based map system shows strong potential for operational deployment, particularly in adverse conditions or environments where cognitive focus is critical. Further testing in realistic field settings is recommended to validate these benefits.

CONCLUSIONS & DISCUSSIONS

This exploratory study offers promising initial evidence for the value of integrating XR as a complementary tool alongside traditional 2D cartographic maps in terrain analysis. By enabling participants to interact with immersive 3D representations of the environment, the XR system provided additional spatial context that supported more intuitive reasoning about elevation and visibility—two critical aspects of terrain understanding.

Across both quantitative and qualitative measures, the XR tool appeared to enhance users' spatial awareness, decision confidence, and task efficiency, while also reducing perceived mental effort and workload. The preliminary results support the hypothesis that the XR system will lead to improved task performance, higher confidence in responses, and lower perceived workload compared to 2D maps.

The results of the current pilot study reinforces the idea that XR should be used to augment and extend conventional map-based training and planning methods rather than as a replacement for 2D maps. While 2D maps remain indispensable for symbolic terrain information (e.g., terrain types, water features, and legends), XR facilitates direct interaction with topography—bridging the gap between abstract representation and embodied understanding.

This has important implications for training and education. Terrain interpretation is a skill that typically requires significant experience to develop. XR offers a dynamic learning environment in which users can experiment, explore, and receive immediate spatial feedback. Participants demonstrated exploratory behaviors—such as walking around the terrain or adopting a first-person viewpoint—that are impossible with static 2D maps but highly beneficial for building mental models of terrain. These behaviors point to XR's potential to foster experiential learning, making it a powerful supplement to classroom-based instruction and mission preparation.

The study also suggests that XR tools may help reduce the cognitive burden associated with terrain analysis for novice users or trainees who have not yet developed strong spatial reasoning skills. By externalizing spatial relationships into a manipulable 3D space, XR can scaffold terrain learning and support a faster, more intuitive grasp of elevation, slope, and line-of-sight.

Some limitations remain, including hardware constraints (e.g. lacking ruggedness), software feature development (e.g. lacking scale indicators, compass, and reset view), and experimental setup (i.e. lacking counter-balanced task conditions, sufficient sample size for statistical power, target participants with military operational backgrounds).

Additionally, there is the need for high-fidelity 3D terrain data that can be accessed through various interfaces, including mobile tablet devices, web browsers, and immersive XR applications (as presented in the current study). The increasing user acceptance of utilizing high-fidelity 3D terrain in daily tasks among operational units helps pave the way for a future where XR systems are routinely used. Participants' high usability ratings and their reflections on operational relevance highlight the potential for XR to be embedded into real-world training pipelines.

In summary, XR terrain visualization holds considerable promise as a training and operational aid—one that complements, rather than competes with, traditional cartographic tools. It offers a flexible and engaging platform for building terrain literacy, improving mission planning, and preparing users for real-world spatial challenges in both training and field environments. The future plan is to visualize additional information layers such as cyber infrastructure and demographics.

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REFERENCES

Bennett, R., Zielinski, D. J., & Kopper, R. (2014). Comparison of interactive environments for the archaeological exploration of 3D landscape data. 67–71. https://doi.org/10.1109/3DVIS.2014.7160103

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In Advances in Psychology (Vol. 52, Issue C, pp. 139–183). https://doi.org/10.1016/S0166-4115(08)62386-9

John, M. S., Harvey, S., Smallman, H. S., Oonk, H. M., & Cowen, M. B. (2000). Navigating Two-Dimensional and Perspective Views of Terrain.

Kim, Y. M., & Rhiu, I. (2024). Development of a virtual reality system usability questionnaire (VRSUQ). Applied Ergonomics, 119(May), 104319. https://doi.org/10.1016/j.apergo.2024.104319

Kuijper, F., & Smelik, R. (2022). A SCALABLE ARCHITECTURE FOR RAPID TERRAIN ANALYSIS. Towards Training and Decision Support for Complex Multi-Domain Operations.

Landis, J. R., & Koch, G. G. (1977). The Measurement of Observer Agreement for Categorical Data. Biometrics, 33(1), 159. https://doi.org/10.2307/2529310

Lester, B. D., Larson, R., Dosch, I., Fowler, G. F., & Rauschenberger, R. (2020). Perception of Terrain Slope in Real and Virtual Environments (pp. 197–203). Springer, Cham. https://doi.org/10.1007/978-3-030-51064-0_26

Li, N., Willett, W., Sharlin, E., & Sousa, M. C. (2017). Visibility perception and dynamic viewsheds for topographic maps and models. Symposium on Spatial User Interaction, 39–47. https://doi.org/10.1145/3131277.3132178

Merritt, J. O., CuQlock-Knopp, V. G., & Myles, K. (1997, June). Enhanced perception of terrain hazards in off-road path choice: stereoscopic 3D versus 2D displays. In Targets and Backgrounds: Characterization and Representation III (Vol. 3062, pp. 101-104). SPIE.

Popelka, S., & Brychtova, A. (2013). Eye-tracking Study on Different Perception of 2D and 3D Terrain Visualisation. The Cartographic Journal, 50(3), 240–246. https://doi.org/10.1179/1743277413Y.0000000058

Savage, D. M., Wiebe, E. N., & Devine, H. A. (2004, September). Performance of 2D versus 3D topographic representations for different task types. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 48, No. 16, pp. 1793-1797). Sage CA: Los Angeles, CA: SAGE Publications.

Sweet, B., & Kaiser, M. (2011, August). Depth perception, cueing, and control. In AIAA Modeling and Simulation Technologies Conference (p. 6424).

Wagner, B., Hoppe, A. H., van de Camp, F., & Maier, S. (2023). An Evaluation of Virtual Reality for Terrain Assessment (pp. 332–339). https://doi.org/10.1007/978-3-031-36004-6_46

Wood, M., Pearson, D. G., & Calder, C. (2007). Comparing the effects of different 3D representations on human wayfinding (pp. 345–356). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-36728-4_26

Zijlstra, F. R. (1993). Efficiency in work behaviour. Delft University, The Netherlands.