Augmented reality in earthquake rescue: impact on workload and decision making

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SUMMARY

This study investigates the application of augmented reality to enhance rescue efficiency, alleviate workload, and improve decision-making in earthquake rescue. The findings demonstrate that AR-based solutions surpass conventional approaches in task completion duration, map utilisation, and decision-making simplicity, underscoring AR's capacity to improve human factors issues in disaster contexts. Future studies should include professional rescue teams as well as more complex simulations to test AR's effectiveness in real-world emergency situations.

KEYWORDS

Augmented Reality, Earthquake rescue, Performance, Workload, Decision making.

Introduction

The utilisation of Augmented Reality (AR) technology in earthquake rescue is a significant advancement in disaster management. Earthquakes frequently produce catastrophic damage, needing an immediate and accurate reaction to find and rescue persons trapped within collapsed structures (Macintyre et al., 2006). Conventional rescue operations are often obstructed by restricted sight, insufficient situational awareness, and communication difficulties. Augmented Reality provides a revolutionary solution by augmenting real-time visualisation, strengthening spatial awareness, and promoting communication among rescue teams. Augmented Reality (AR) overlays digital information onto the physical world, allowing rescuers to effectively “see through” debris, map unreachable zones, efficiently coordinate operations Hu et al. (2022) and more generally improve rescue personnel’s perceptual abilities (Demirkan & Duzgun, 2020; Xu et al., 2024). AR technology features such as head-mounted displays and interactive interfaces, have the potential to revolutionise the way search and rescue efforts are done in difficult and complicated places.

Several studies have emphasised the use of augmented reality in improving situational awareness, and navigation among rescue workers. For example, a system that combines ground-penetrating radar (GPR) and AR, such as the framework proposed by Hu et al. (2022), can support the visualisation of voids beneath disaster debris in 3D. This method was shown to dramatically enhance the efficiency and safety of searching for survivors trapped inside collapsed structures (Hu et al., 2022). Xu et al. (2024) investigated the application of multi-user AR platforms to facilitate team-based search and rescue operations. Their findings suggest that during search and rescue (SAR) missions, combining an exocentric navigation perspective with synchronised spatial data can improve collaboration efficiency. Chalimas and Mania (2023) proved the usefulness of a cross-device AR system that combines thermal imaging and GPS tracking to aid in firefighting and rescue operations. Finally, the importance of sophisticated communication technology in AR systems is particularly worth noting, as it can significantly improve the intelligence exchange capabilities of rescue teams. Wang et al. (2023) presented a 5G-enabled augmented reality architecture for exchanging real-time information during emergencies. This technology enables seamless data sharing between rescue teams and medical facilities, resulting in rapid and informed decision-making.

Based on previous research, AR has increased rescue efficiency, safety, and teamwork by improving perception and information aggregation. However, there is a lack of research on using AR in large-scale disasters like earthquakes. Therefore, this study focuses on earthquake rescue and explores whether AR can impact human factors issues in earthquake rescue.

Methodology

This study investigated the benefits of AR in earthquake rescue scenarios using a simulated virtual environment. A virtual earthquake environment was created with Unity 3D, and participants performed tasks in two modes: an AR-based system with holographic image map and 3D marking system and a traditional system similar to paper/digital maps. The study used a within-subject design, with participants receiving instruction on judging the level of building damage before the experiment. NASA-TLX was used to record performance measures such as task accuracy, completion time, and workload evaluation. Following the experiment, key decision analysis on the marking process was performed using video recordings of the experimental method and participant interviews to assess the decision-making process. Data from Unity logs and participant itineraries aided both quantitative and qualitative analyses of rescue performance. Research questions: Can AR offer advantages in workload, work memory and decision making in emergency rescue?

Participants

This study publicly recruited 20 ordinary participants through the internet. All participants conducted the experiment individually. Each participant was required to participate in both traditional rescue mode and AR-based earthquake rescue experiments. The order of participating in these two experiments was randomised to control for order effects. The basic information of the participants is as follows:

- Age: 18 - 65
- Gender: Both male and female
- Background: No professional rescue experience

Materials and Equipment

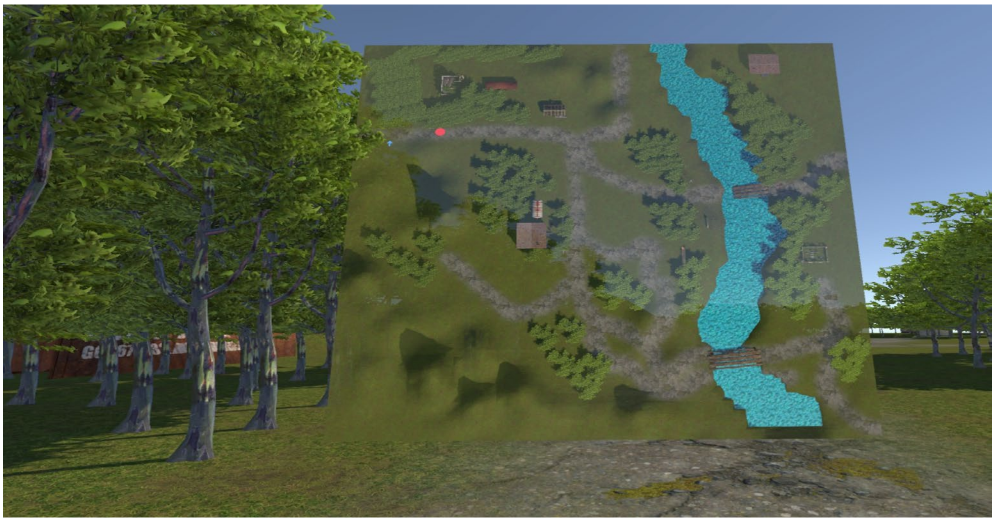

Figure 1: Mountain Village Earthquake Scene Completed Based on Unity 3D

- Virtual Environment: Mountain village earthquake scenes developed using Unity 3D, including multiple houses, collapsed buildings, rivers, bridges, and forests (Figure 1).
- Quest VR headset: Through the Quest VR headset, participants can immerse themselves in virtual earthquake rescue scenes and interact with the virtual environment.
- NASA-TLX questionnaire: Used to evaluate participants' perceived workload after the experiment.
- Data recording tool: Real time recording and uploading of participants' task completion time, walking path, and decision-making process data to the researcher's Raspberry Pi server.
- Interview tools: Conduct interviews using CDM Pro and experimental videos to collect participants' subjective feelings and key decision points in the decision-making process.

Design

This study uses a within-subjects design, with the independent variable being the rescue mode type, which includes:

- **Traditional Rescue Mode**: Use traditional maps (Figure 2) (digital maps) and marking on maps.
- **AR-based Rescue Mode**: Use AR map (Figure 3) (a translucent map that can be displayed in front of you at any time) and use AR technology to mark directly on the building.

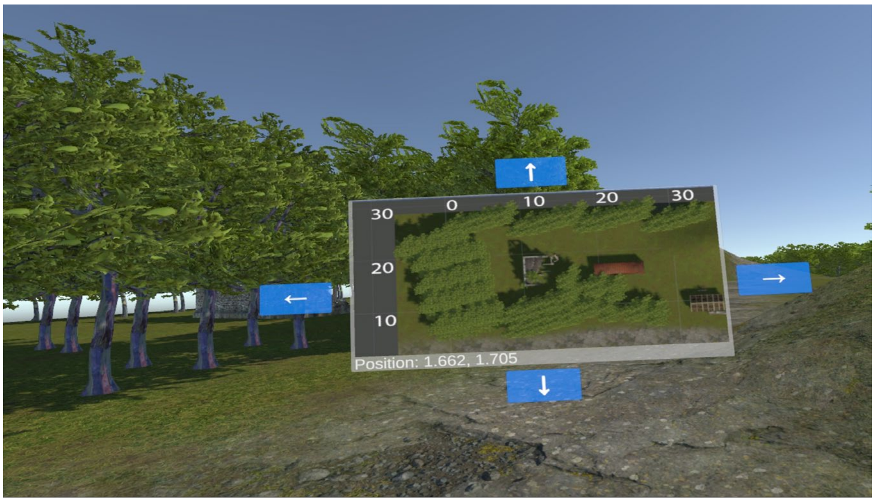

Figure 2: Traditional map

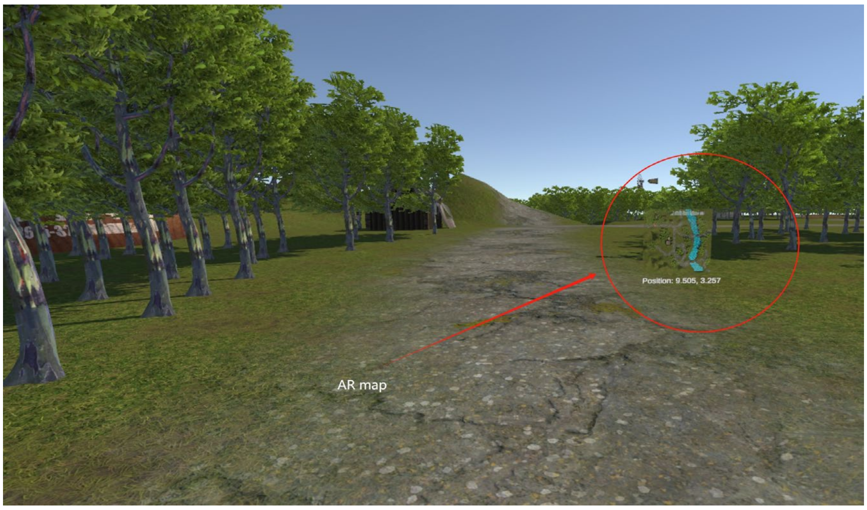

Figure 3: AR map

Reliability and Validity

To ensure the reliability and validity of the research results, the following measures were taken in this study:

- Internal reliability: By adopting a within-subject design, each participant engages in both rescue modes, thereby minimising the impact of individual differences.
- Randomization: The order of experimental conditions is randomly assigned to control for order effects.
- Standardisation procedures: The experimental process and task instructions are strictly standardised to ensure that all participants conduct the experiment under the same conditions.
- Multiple data sources: Combine quantitative and qualitative data to provide a comprehensive analytical perspective and enhance the validity of the results.
- Reliability of questionnaire: Utilise the validated NASA-TLX questionnaire to ensure the reliability and consistency of workload assessment.
- Interview reliability: Interviews were conducted using the CDM-Prob method to ensure systematic and consistent data collection.

This study uses these parameters to assure the trustworthiness of experimental data and the effectiveness of conclusions, thereby providing a sound scientific foundation for the use of augmented reality technology in earthquake rescue.

Result

The performance metrics show that the AR system outperforms traditional systems in every aspect of rescue operations. Statistical analysis using a paired-samples t-test shows that the AR system significantly reduces task completion time (t(df)=8.710, p=0.000, Cohen's d=1.948), indicating a significant improvement in efficiency. This effect is both statistically significant and practically meaningful, as Cohen's d value indicates a very large effect size. Furthermore, the AR system contributes to a moderate but significant increase in the number of correct labels for damaged buildings (t(df)=-2.096, p=0.050, Cohen's d=-0.469). Although this result is marginally significant, more research is required to confirm its impact.

In addition, the AR system decreased the frequency with which rescue personnel opened maps (t(df)=8.669, p=0.000, Cohen's d=1.938), making the task more fluid and requiring less cognitive effort. It also reduced the amount of time spent viewing maps (t(df)=6.737, p=0.000, Cohen's d=1.506), allowing for better access to critical information. The reduction in map usage time resulted in faster decision-making and task completion.

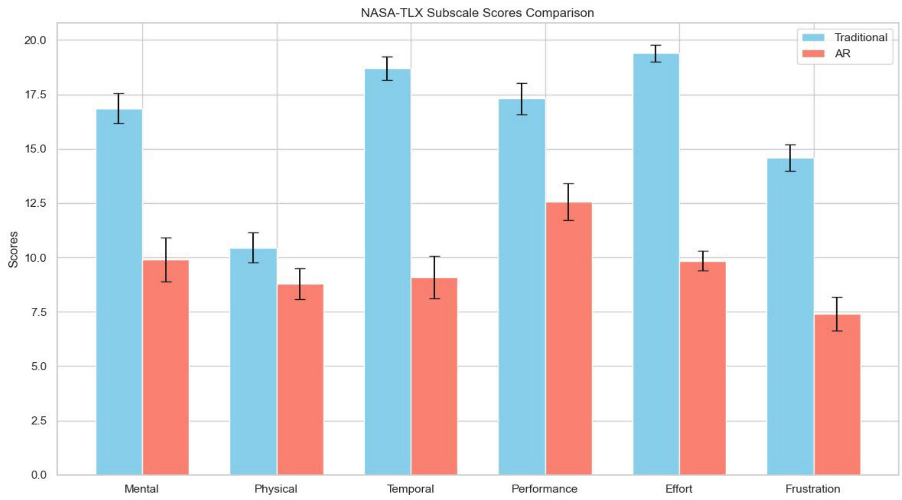

Figure 4: Comparative Bar Charts of NASA-TLX Subscale Scores for Traditional and AR Rescue Systems

Furthermore, the AR system significantly reduced the total walking distance required to complete the rescue mission (t(df)=3.215, p=0.005, Cohen's d=0.719), indicating that it is effective at optimising rescue routes and reducing unnecessary movement. Finally, workload assessment using the NASA-TLX scale revealed a significant decrease in perceived workload (t(df)=11.291, p=0.000, Cohen's d=2.525) (Figure 4), demonstrating the AR system's positive impact on reducing mental and physical strain. The reduced workload may result in decreased fatigue and improved long-term performance, benefiting the overall well-being of rescue personnel. These findings highlight the practical benefits of AR technology in increasing the efficiency, accuracy, and overall experience of rescue operations.

Decision-Making Process

Each participant was obliged to choose the same decision point for discussion in two experimental conditions: traditional map and AR-based search and rescue. Twelve participants decided to discuss the "marking buildings" decision-making process, while the remaining eight participants chose route planning as the major decision point for discussion. Uncertainty: 100% of the participants reported that they felt uncertain during the decision-making process owing to inadequate knowledge, time constraints, and the potential dangers linked with the repercussions of their choices. For example, one participant stated, "I continually checked if there were any stranded folks outside the house. I could view virtually the entire home via all of the windows, but I didn't notice any imprisoned people. I wasn't sure if I should identify this house as requiring additional searches or if there were any captive people. If I designated it red when there were no trapped persons, it would be a waste of our scarce medical resources. Another participant stated, "At the intersection, I needed to choose a bridge based on the map, but I had no idea which bridge was passable, and time was short. I needed to make the appropriate decision here so that I could search the entire impacted village more swiftly." This uncertainty becomes an obstacle to their decision-making, making it difficult for decision-makers to determine whether the outcome is "correct" or "helpful".

Decision Differences Between Two Rescue Methods: During the decision-making process for designating buildings, eight participants reported challenges with traditional map marking. For example, one participant commented, "After opening the map, I had to shift it left and right several times to locate the location of the building to be marked based on the coordinates and adjacent plants and structures. This put pressure on me." In the AR experiment, all 12 participants stated that after evaluating the building's damage condition, they just needed to select whether to designate the building as requiring further search, without having to constantly check the map, resulting in no decision-making issues.

Five of the participants who made route planning decisions reported feeling less pressure to make decisions throughout the AR experiment. Three participants reported that traditional map searches required more time to validate their position on the map and plan their next path. For example, one participant stated, "In the typical map experiment, I had to open the map numerous times and repeatedly check my location based on coordinates and the environment, as well as seek for adjacent structures that required searching. This was a huge waste of my time and energy. I couldn't see the house immediately when I was looking for the last structure on the other side of the river because trees were in the way. As a result, I checked the map five or six times during the search, wasting one minute. Ultimately, due to the ten-minute time limit, I failed to finish marking the building."

AR technology dramatically improves decision-making by delivering real-time information overlays and visual aids. When participants employ AR technology, they can make faster and more accurate decisions, saving time and cognitive strain from inadequate information and map scanning. This not only improves rescue efficiency but also increases decision accuracy and consistency.

Discussion

The findings of this study show that augmented reality (AR) technology offers substantial advantages over traditional rescue modes (TR) in earthquake rescue. First, AR technology shines at greatly lowering the workload of rescue personnel. According to the NASA-TLX questionnaire evaluation, participants using the AR system reported significantly lower workload across multiple dimensions than those using the traditional system, with Cohen's d reaching 2.525, indicating that AR technology has a significant impact on reducing cognitive and physical stress. This discovery is consistent with the research results of Alessa et al. (2023), which imply that AR technology can effectively reduce users' cognitive burden through real-time information overlay. Second, AR technology has considerably enhanced rescue efficiency, as indicated by shorter completion times and overall walking distance. Participants finished the task in an average of 201 seconds less while utilising the AR system, with a Cohen's d of 1.948, indicating a significant effect. Furthermore, the overall walking distance was reduced by roughly 65.36 meters, with an effect size of 0.719, indicating a modest impact. These results suggest that AR technology can enhance the overall efficiency of rescue operations by optimising rescue routes and reducing unnecessary movement, similar to the findings of Brizzi et al. (2018), who discovered that AR technology can significantly improve the speed and accuracy of task execution. In terms of decision-making, AR technology dramatically minimises the uncertainty that rescue professionals confront by delivering real-time spatial video feedback and information overlay, increasing decision-making speed and accuracy. Participants reported that AR technology enabled them to determine whether there were trapped individuals within buildings more rapidly, saving time and effort spent continually checking maps. This is congruent with the research conducted by Mitaritonna and Abásolo (2015), which demonstrates that AR technology can boost users' situational awareness and decision-making abilities, hence improving the overall task execution efficacy.

In addition, AR technology has improved the frequency and duration of map use. When participants utilise the AR system, they see fewer maps and spend less time looking at them. This not only improves the efficiency of information gathering, but it also reduces cognitive strain, allowing rescue personnel to concentrate on the actual rescue duties. However, in terms of accurately labelling the number of damaged structures, the AR system had a moderate influence (Cohen's d = -0.469), but its significance was only marginal. This finding requires additional research verification.

In conclusion, this study shows that AR technology has tremendous potential for use in earthquake rescue. It not only increases rescue efficiency and reduces workload, but it also improves decision-making. However, the study has some drawbacks, including a limited sample size and simulation limits in the experimental context. Future studies should increase the sample size and test AR technology in more realistic rescue scenarios to further validate its usefulness. Furthermore, the use of AR technology in various types of rescue activities and environmental elements should be investigated in order to completely grasp its benefits and limitations.

Impact of decision-making process

AR technology improves the decision-making process of rescue personnel by increasing situational awareness and information sharing. Participants noted that the AR system's real-time spatial video feedback enabled them to get a more thorough picture of the on-site scenario, eliminating uncertainty caused by limited information and allowing them to make more timely and correct decisions. This finding is consistent with study undertaken by Martins et al. (2022), which demonstrates that AR technology can boost users' decision-making efficiency and accuracy by giving instant environmental information.

Significant reduction in workload

The NASA-TLX questionnaire assessment revealed that AR devices greatly lower the perceived workload of rescue personnel. Specifically, after using the AR system, participants reported a considerable reduction in both cognitive and physical workload, with Cohen's d reaching 2.525. This finding suggests that AR technology has a high practical application value in relieving the work pressure and weariness of rescue personnel. Similar research has proven that AR technology can greatly reduce users' burden by delivering straightforward information display and lowering operational complexity (Alessa et al., 2023).

Significant improvement of rescue efficiency

The considerable reduction in completion time and total walking distance suggests that augmented reality technology can significantly improve the efficiency of rescue operations. Participants who utilised the AR system completed tasks faster and travelled shorter distances within the virtual world, demonstrating the efficiency of AR technology in optimising rescue routes and avoiding wasteful movement. This is consistent with the findings of Liu et al. (2023), which imply that AR technology can considerably enhance job execution efficiency through real-time navigation and route optimisation.

Optimisation of decision process

AR technology excels at optimising decision-making processes. When employing an AR system, participants may make judgements faster and more correctly, saving time and cognitive strain from frequent map checks.

Optimisation of map use

AR technology has dramatically reduced the frequency of map viewing and usage time, showing that rescue professionals can receive and use critical information more efficiently. This not only improves rescue efficiency but also reduces cognitive strain, allowing rescue professionals to concentrate more on the actual rescue duties. According to Qiu et al. (2024), AR maps are more effective than 2D maps for gaining spatial knowledge. AR displays are essential for helping people learn about sights and routes. The upgraded map broadens the scope of spatial information beyond the centre and highlights landmark sites to provide comprehensive information about the environment; hence, the improved map can aid in the acquisition of spatial knowledge.

Properly marked edges are significantly raised

Although the AR system had only a moderate influence on accurately labelling the number of damaged buildings (Cohen's d = -0.469), and its significance was just marginal (p = 0.050), this result suggests that AR technology has the potential to improve labelling accuracy. One possible explanation is that real-time information and visual support offered by AR technology assist rescue responders in more correctly identifying and labelling damaged buildings. However, because the p-value is merely on the edge of significance, future research should increase the sample size to confirm this effect.

Comprehensive discussion

Overall, this study shows that the use of AR technology in earthquake rescue offers considerable benefits. It improves rescue efficiency, decreases workload, and optimises decision-making. These findings are consistent with previous research, supporting the promise of AR technology in complex and dynamic contexts. However, the study has certain drawbacks, including a limited sample size and simulation limits in the experimental setting. Future studies should increase the sample size and test AR technology in more realistic rescue scenarios to further validate its usefulness. Furthermore, the use of AR technology in various types of rescue activities and under varied environmental conditions should be investigated in order to fully grasp its benefits and limitations.

Practical significance

The study's findings suggest that AR technology has tremendous potential for use in earthquake rescue. AR technology can significantly improve rescue efficiency by reducing task completion time and optimising rescue routes, allowing for the rapid rescue of more trapped individuals in emergency scenarios. Furthermore, the reduced workload reduces weariness and tension among rescue professionals, allowing them to perform more consistently while still maintaining their mental health. AR technology improves rescue personnel's decision-making ability and accuracy by overlaying real-time information and optimising decision-making points, eliminating erroneous decisions due to incomplete information. Simultaneously, eliminating unnecessary map reading and walking distance allows for more effective allocation of limited medical and rescue resources, thus boosting total rescue effectiveness.

Research limitations and future research directions

Although this study reveals the considerable benefits of AR technology in earthquake rescue, it also highlights certain limitations and suggests areas for future research. First and foremost, this study included a sample size of 20 participants. Although the results were significant, a bigger sample size study might help to validate and extend these findings. Second, this investigation was carried out in a virtual setting. In the future, AR technology should be tested in real or more realistic rescue scenarios to determine its true performance in complicated and dynamic surroundings. Furthermore, future research might look into the effects of AR technology in different sorts of rescue tasks and under varied environmental conditions to better understand its benefits and drawbacks. Future research should focus on the effectiveness of AR technology in long-term rescue missions, including its effects on the continuing work abilities and mental health of rescue professionals. Finally, investigating how to improve the functionality and user interface of AR technology to better suit the needs of rescue personnel in various scenarios will contribute to AR technology's practicality and application effectiveness.

Conclusion

This research confirms the potential of augmented reality (AR) to improve the efficacy of rescue operations, reduce workload, and improve decision-making. Compared to traditional approaches, AR-based tools allow participants to perform rescue missions faster while reducing the psychological (workload) burden. However, limitations of this study include the use of non-professional volunteers and the experiment's short duration, which may not accurately reflect the intricacy of real-world rescue attempts. Future study should include professional rescue teams, more complicated scenarios, and longer experimental periods in order to properly evaluate AR's usefulness and develop AR-based rescue tactics for practical use.

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