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Volumetric Hazard Visualization and Navigation in Simulated Augmented Reality

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14. ABSTRACT
Three-dimensional environmental hazards, such as dangerous chemicals, biological agents, or radiation, may often be invisible to the human eye. Enabling Warfighters and other personnel to navigate potentially dangerous environments safely requires conveying the locations of these hazards: in short, making the invisible visible. Ideally, 3-D hazard information should be conveyed in a manner that can be rapidly understood while also minimizing interference with navigation or other sensory and attentional tasks. We therefore performed a test of three different potential visualization methods that could be used with augmented reality heads-up displays, examining the effectiveness of these displays on navigational efficiency and on simulated safety during a search and navigation activity. This report summarizes the development of the visualizations, the user study, and the general findings. Results suggest the relative performance of different visualizations is likely situation-specific. Overall, the 3-D visualization resulted in the most-efficient navigation, as shown with shorter travel path lengths. However, the 2-D visualization and the combined 2-D and 3-D visualization yielded efficiency and safety benefits in certain environmental configurations. These results can inform future research, design, and use recommendations for visualizing 3-D hazards in heads-up displays.

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Humans in Complex Systems, Network and Computational Sciences, augmented reality, uncertainty visualization, volumetric display, 3-D hazards, AR in VR, wayfinding, virtual environment

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1. Introduction

In military operations, a variety of hazards may be encountered. Some of these are 2-D (i.e., they can be marked on a flat map or display, such as the estimated location of an explosive device or an enemy outpost). Other hazards, such as clouds of invisible chemical or biological agents, are 3-D (volumetric). It is not known how to best mark these hazards and make them identifiable to Warfighters and mission planners. The current state of the art is to portray 3-D hazards and their uncertainties in a 2-D fashion by projecting hazard levels down onto a flat plane. This planar representation is then shown on a map or in an augmented reality heads-up display.

In discussions with the Defense Threat Reduction Agency (DTRA) Digital Battlespace Management Division's chem-bio group, a need was expressed for better visualization of invisible volumetric hazards. We therefore performed a study to assess different forms of visual representations of invisible hazards. Particularly, we saw the need to assess visualization methods that can convey the height and dispersion of hazards while still clearly conveying their location in the 2-D ground plane and allowing efficient navigation. Inspired by our group's work on uncertainty visualizations (Kusumastuti et al. 2022) and immersive environments (Pollard et al. 2020), we sought to develop 2- and 3-D representations of volumetric hazards in a simulated augmented reality virtual environment and examine how the different visualizations affected user performance.

To address this question, the US Army Combat Capabilities Development Command Army Research Laboratory and California State University, Los Angeles collaborated to develop visualizations, create a test environment, and conduct a user study (see Siriwardena [2022]). This report summarizes the construction of the visualizations, the user study, and its findings.

2. Methods

2.1 Visualizations

Two types of visualizations were developed. One, a 2-D projection visualization, uses color indicators on the ground to represent hazard levels in the area above the ground at that location (Fig. 1a). Two-dimensional ground projections are the current state of the art for visualizing volumetric hazards in the military. A major benefit of such a visualization is that the visualization conveys hazard information without impeding the user's forward or peripheral view as they navigate the environment. However, a ground projection can be misleading, as the color represents the hazard levels in any space in the column above a given point (i.e., an elevated hazard might be safe to navigate underneath, but a ground projection would not provide enough information for a user to know this). The second visualization, a 3-D volume representation of colored surfaces (Fig. 1b), visually depicts the location and elevation of the hazards. The main benefit of this type of visualization is that it clearly conveys an additional dimension of relevant data—hazard elevation—that can be useful for safe and efficient navigation of the environment. However, the 3-D representations can lead to more visual clutter on the augmented reality display and may obstruct the user's view of relevant objects or pathways. We used both these visualizations as conditions in our study. A third visualization condition included the 2- and 3-D visualizations shown simultaneously (Fig. 1c).

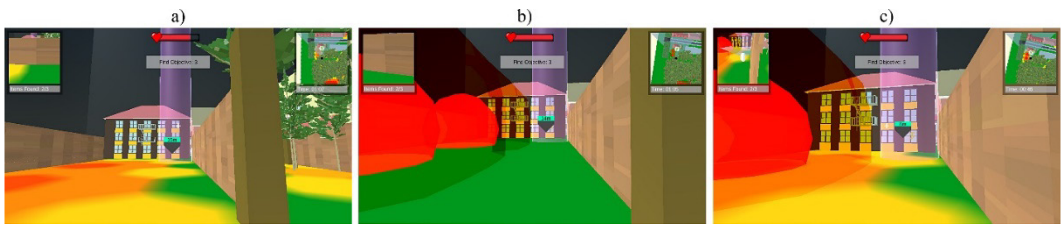

Fig. 1 Visual representations of otherwise invisible volumetric hazards: a) 2-D ground projection, b) 3-D surfaces representation, and c) both together. Each of these was used as a test condition in the study.

2.2 Test Environment and Task

The test environment was developed in the Unity game engine. The environment depicts a small section of a fictional town with a main street, houses, yards, and a forest. To encourage users to navigate in the environment, target objects were placed in different locations and were required to be collected in succession. These target objects could be found by taking more than one path. Into this environment, volumetric hazards were strategically placed in locations such that particular visualizations' drawbacks would be relevant to game play. For example, an elevated volumetric hazard was placed in an alleyway, providing a test case for how users would treat this hazard in the different visualization conditions (Fig. 2).

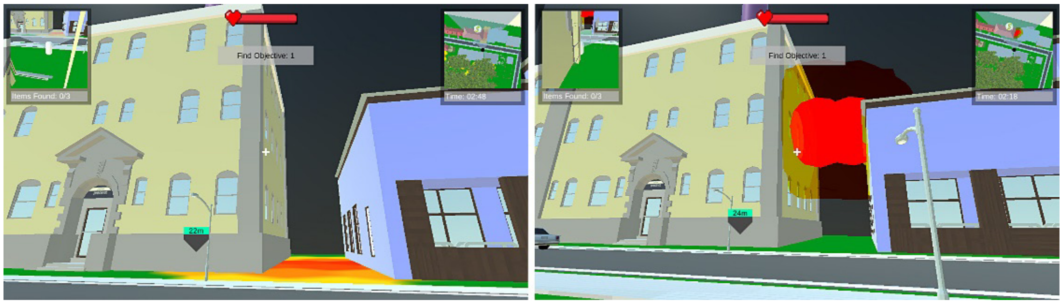

Fig. 2 The 2- and 3-D visualizations in an area of the game. This alleyway in the game environment is partially obstructed by an elevated volumetric hazard, but it is safe to travel underneath the hazard. This is more evident in some visualizations than others.

We predicted that users in the 2-D-only condition would tend to avoid this alleyway, because the ground projection would suggest that the alleyway was unsafe. Instead, users might take a more circuitous route to collect the target object. We predicted the opposite for the 3-D and 2-D+3-D condition, because the user would be able to see that they could safely pass underneath the elevated hazard.

In another example, we placed a series of ground-level hazards in a stretch of backyard such that the 3-D visualizations would obstruct the user's view of the target object and of a safe path to reach it (Fig. 3). We predicted that users in the 2-D condition, who could see a safe path more clearly, would more quickly or more safely navigate this area than those in the 3-D or 2-D+3-D condition.

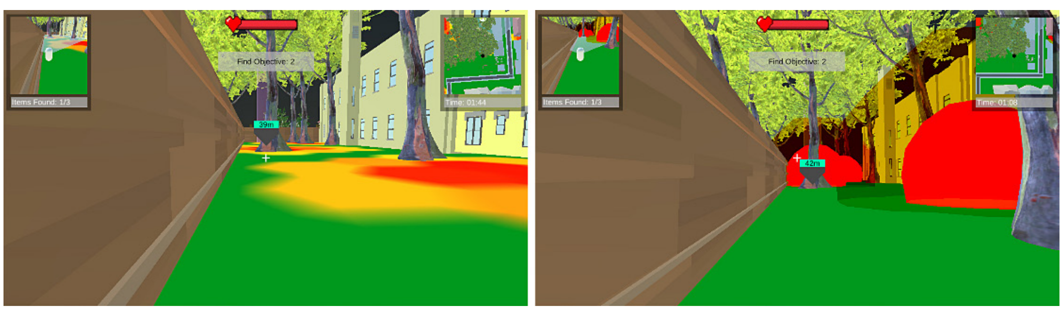

Fig. 3 The 2- and 3-D visualizations in an area of the game. A backyard with multiple ground-level hazards creates a complex zig-zag path that must be traversed to avoid taking damage in this area. This is more evident in some visualizations than others.

The virtual environment is intended to simulate an augmented reality display. It therefore also includes a simulated heads-up display with useful information, including a snippet of an overhead map, a small behind-the-shoulder view, a health bar, next objective, progress, and a time counter. The display also includes a position estimator that shows the current distance (in meters) from where the user is to the target.

2.3 Procedure

We conducted the study online. Participants were recruited via the platform Prolific and they engaged with the simulated augmented reality environment online (see also Files et al. [2022]). Inclusion criteria were age 18 years or older, fluency in English, normal or corrected-to-normal vision, normal color vision, and the use of a suitable screen, pointing device, and browser. Using their own computers, participants accessed our test environment as a web-based game-like application. After providing consent and confirming that they met the eligibility criteria, the participants engaged with a brief tutorial built into the application. They then navigated three game levels of the virtual environment and collected target objects in that environment while trying to avoid simulated damage from visualized volumetric hazards. Contacting a hazard would cause the screen to flicker and the health bar to decrease for as long as the player continued to contact the hazard.

A between-subjects design was used, with each participant only seeing one visualization condition from the following: 1) volumetric hazards projected onto the ground plane as 2-D visualizations, 2) volumetric hazards depicted as 3-D volumes in the environment, and 3) volumetric hazards depicted both ways simultaneously. Ninety participants took part in the study, 30 for each visualization. The time taken to complete stages of the task, damage taken during the task, and path lengths while completing the task served as performance variables. The data violated assumptions of parametric tests, so nonparametric tests (Kruskal-Wallis tests followed by post hoc pairwise Mann-Whitney U tests) were used to compare conditions. For brevity, only significant pairwise comparisons are reported here. Counts of participants who chose different routes or strategies were also used to compare conditions.

3. Results and Conclusion

When comparing over the entire game performance, median path length was found to be shorter in the 3-D visualization condition as compared to the 2-D+3-D condition and 2-D condition (Mann-Whitney U tests for pairwise comparisons found median path length to be shorter in the 3-D condition [Mdn = 179.1] as compared to the 2-D+3-D condition [Mdn = 204.4, U = 596, z = 2.160, p = 0.031] and marginally shorter as compared to the 2-D condition [Mdn = 207.2, U = 327, z = –1.818, p = 0.069].) This suggests that the 3-D visualization allowed users to take more direct routes by going underneath elevated hazards. It is interesting that the 2-D+3-D condition did not also yield shorter paths, but it is possible that viewing the 2-D ground display at the same time as the 3-D display might have made areas seem more dangerous than they really were, perhaps just due to the sheer amount of red on the screen.

Examining performance variables on key areas of the environment was more revealing of different user strategies and performance. As previously mentioned, the hazard visualization in the alleyway provided an opportunity to evaluate how participants chose a path under different visualization conditions. Participants could take the shorter path through the alley that contained the hazard visualization. Alternatively, they could take a more roundabout, longer path that avoided hazards. For the alley objective, the 3-D visualization led to significantly faster completion times than the other conditions (Mann-Whitney U tests showed the 3-D condition [$Mdn = 18.5$] yielding a significantly lower median time than the 2-D [$Mdn = 37.5$, $U = 168.5$, $z = -4.162$, $p < 0.001$] and 2-D+3-D [$Mdn = 29.5$, $U = 663$, $z = 3.149$, $p = 0.002$] conditions. The 2-D+3-D condition tended to have shorter completion times as compared to the 2-D condition [$U = 329$, $z = -1.789$, $p = 0.074$]). For the alley objective, the 3-D visualization also led to significantly shorter paths as compared to the other two conditions (3-D condition median path length [$Mdn = 61.1$] was significantly shorter than in 2-D [$Mdn = 207.5$, $U = 153$, $z = -4.391$, $p < 0.001$] and 2-D+3-D conditions [$Mdn = 202.8$, $U = 757$, $z = 4.539$, $p = 0.001$]). In addition, significantly more participants entered the alley with the 3-D condition compared to the other conditions. This suggests that, as predicted, participants took a more circuitous route to the target (avoiding the alley) when they could not clearly see that they could walk under the hazard. Significantly fewer participants entered the alley in the 2-D+3-D condition compared to either visualization alone, consistent with the possibility that the combined visualization increased the apparent danger of areas relative to either visualization alone. Figure 4 shows paths of each user by whether they entered or avoided the ally and by condition.

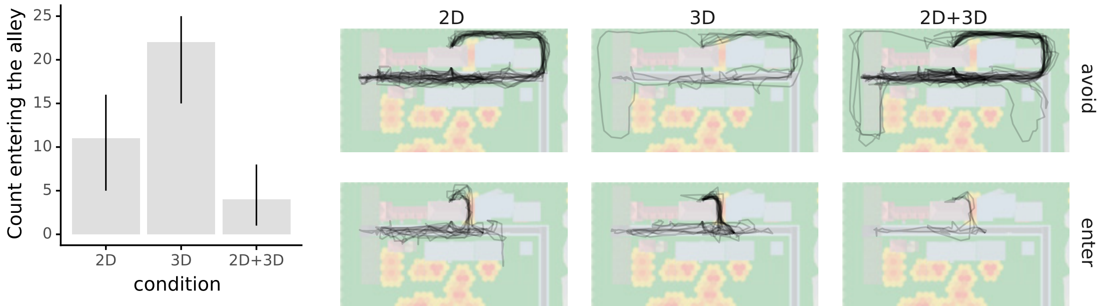

Fig. 4 **(Left) Counts with bootstrapped 95% confidence intervals of participants entering the alley, by visualization condition. (Right) Overhead map diagrams of the environment with participant paths highlighted. The alley is the vertical stretch between a row of buildings at the top. For each visualization condition (2-D, 3-D, and 2-D+3-D, respectively), each black line represents the path of a single user who chose to travel through the alley to the relevant target. More participants chose to traverse the alleyway in the 3-D condition than in the other conditions.**

For the backyard objective, no significant differences were found for path length, time taken, or amount of damage taken across the three conditions. However, more participants in the 3-D condition took damage during the backyard objective than in the other two conditions. Figure 5 shows paths of each user by whether they took any damage while seeking the backyard objective. This suggests that, as predicted, participants had a more difficult time identifying the safe path through the backyard in the 3-D condition, perhaps because the 3-D visualization was obstructing their view. However, the combined 2-D+3-D condition was as equally obstructive as the 3-D condition and was not associated with an increase in participants taking damage.

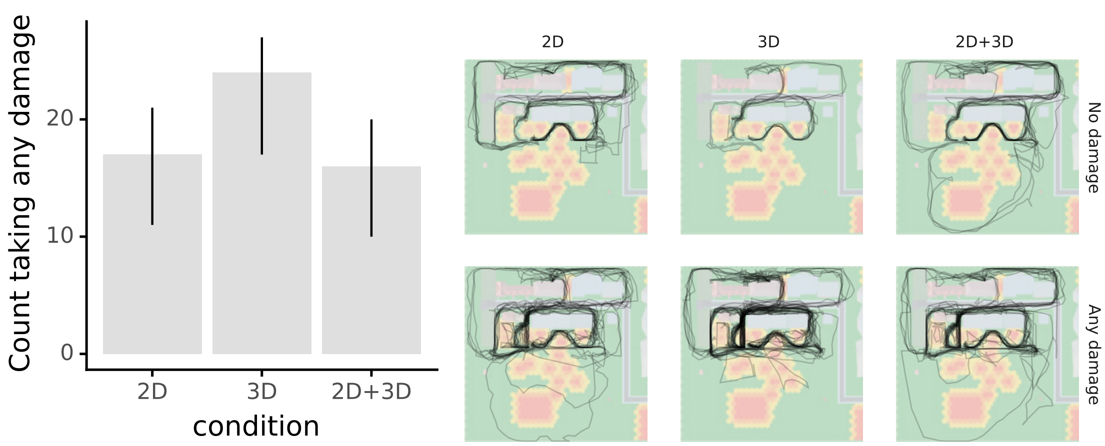

Fig. 5 **(Left) Counts with bootstrapped 95% confidence intervals of participants taking damage while pursuing the backyard objective, by visualization condition. (Right) Overhead map diagrams of the environment with participant paths highlighted. More participants took damage pursuing the backyard objective in the 3-D visualization condition.**

Although not specifically designed to test the effects of visual obstruction, another area also revealed meaningful differences in behavior across the visualizations. The forest area of the map included a high density of hazards. Getting from the last objective to the exit in the first level required participants to navigate this forest area. Similar to the results of the backyard objective, more participants in the 3-D visualization took damage in this segment compared to the other two visualizations. Examining the paths participants took (Fig. 6) reveals that many participants in the 3-D visualization identified a direct path to the exit that required briefly taking damage.

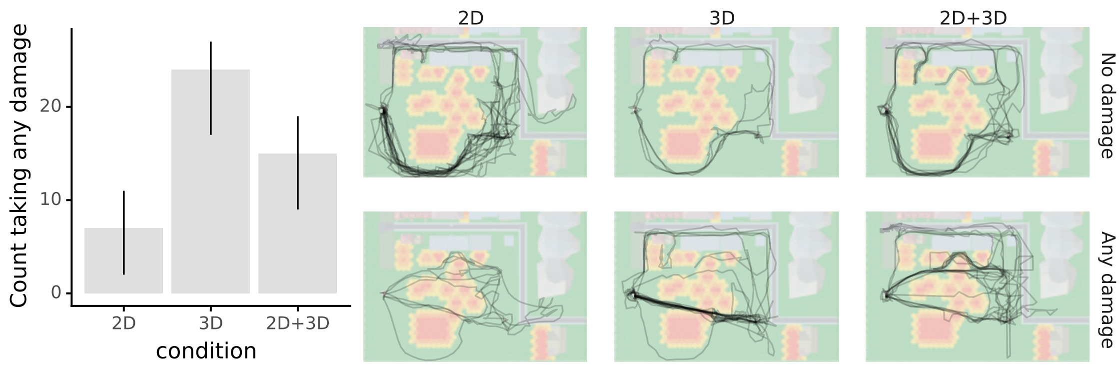

Fig. 6 (Left) Counts with bootstrapped 95% confidence intervals of participants taking damage while navigating the forest area, by visualization condition. (Right) Overhead map diagrams of the environment with participant paths highlighted. Participants in the 2-D condition largely navigated around the forest hazards; many in the 3-D condition took damage passing through a small hazard blocking a direct path to the exit; and in the 2-D+3-D condition, a mix of approaches are apparent.

Our study was an initial exploration into the costs and benefits associated with different methods of visualizing volumetric hazards in simulated augmented reality. Overall results suggest that a 3-D visualization may reduce travel path lengths, likely due to users' enhanced ability to choose more efficient routes when hazard elevation information is clearly displayed. More research is needed to better understand how these different visualization approaches induce different strategic approaches to our task. We observed different behaviors with the 2-D visualization compared to the 3-D visualization but combining them did not always result in a best-of-both-worlds situation.

Volumetric hazards are an important concern for Warfighters, safety personnel, and industry workers, as harmful gases, pathogens, or radiation are often invisible yet need to be avoided for safety. Representing these sorts of hazards in an augmented reality display is one way to help keep personnel safe while operating in these environments. In environments with relevant verticality (as in urban and subterranean environments), representing volumetric hazards in three dimensions might be critical for successful navigation and hazard avoidance, and this work suggests the 3-D visualization we used might address this critical need.

Our basic research in this domain can inform development of future augmented reality hazard visualizations and provide insights on the use of augmented perception in wayfinding. Furthermore, it helps address a need expressed by the DTRA's chem-bio group for better visualizations of volumetric hazards. For more information on this study, see Siriwardena (2022).

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