AIS Transactions on Human-Computer Interaction

Volume 13 | Issue 2 Article 1

6-30-2021

Virtual Reality for Hazard Mitigation and Community Resilience: An Interdisciplinary Collaboration with Community Engagement to Enhance Risk Awareness

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Recommended Citation
Stone, N. J., Yan, G., Nah, F. F., Sabharwal, C., Angle, K., Hatch, F. E., Runnels, S., Brown, V., Schoor, G. M., & Engelbrecht, C. (2021). Virtual Reality for Hazard Mitigation and Community Resilience: An Interdisciplinary Collaboration with Community Engagement to Enhance Risk Awareness. *AIS Transactions on Human-Computer Interaction, 13*(2), 130-144. https://doi.org/10.17705/1thci.00145
DOI: 10.17705/1thci.00145

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Transactions on Human-Computer Interaction

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Available at http://aisel.aisnet.org/thci/vol13/iss2/1

Transactions on Human-Computer Interaction

Editorial DOI: 10.17705/1thci.00145 ISSN: 1944-3900

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Abstract:

To achieve community resilience and mitigate the consequences of natural hazards, community officials must balance competing priorities for local resources and funding. Besides the challenge of dealing with multiple competing priorities, community officials face another challenge: low risk awareness of natural hazards by the public and other stakeholders. Considering that virtual reality (VR) has been used to enhance learning and to change attitudes and behaviors, animating natural hazards in VR has the potential to enhance stakeholders' (e.g., the public, local/state/federal governments, insurance agencies, and property owners) risk awareness. Informed stakeholders make better decisions related to protective action. Therefore, we propose using VR to create a sense of presence and immersion that can provide stakeholders with hazard exposure, demonstrate a hazard's personalized consequences, and simulate the consequences of protective action, which, in turn, can influence attitudes and behavioral intentions of the general public to take protective action. Researchers could also apply VR to other hazardous or life-threatening situations and use interdisciplinary research to identify best methods to develop realistic and credible VR that all citizens can access to help mitigate hazards and enhance community resilience.

Keywords: Virtual Reality, Hazard Mitigation, Community Resilience, Risk Awareness, Natural Hazards.

Dennis F. Galletta was the accepting senior editor for this paper.

1 Introduction

Humanity faced many disasters in 2020. Aside from the coronavirus pandemic, wildfires in California burned more than four million acres, and the Atlantic Ocean experienced so many storms in 2020 that the World Meteorological Organization exhausted the 21 Latin alphabetic letters reserved for naming storms, which required it to use 9 Greek alphabetic letters. The 2020 season produced 30 named storms, 13 of which progressed into hurricanes. In 2020, 262 people were killed in 22 weather disasters and the cost incurred for each disaster was more than US$1 billion (NOAA, 2021). Global warming continues, resulting in climate change (U.S. Global Change Research Program, 2018). In the future, we will likely face more intense wildfires, more powerful hurricanes, and more prolonged heat waves. To reduce injuries, fatalities, and property losses, we need to conduct interdisciplinary research with community engagement to mitigate the damage that natural hazards cause. Natural hazards include (among other things) extreme winds or storms (e.g., hurricanes, tornadoes, downbursts, and thunderstorms), floods, earthquakes, wildfires, and extreme heat.

To protect the community from natural hazards, community officials must understand hazard risks and cost-effective ways to mitigate potential hazards in order to determine how best to allocate local resources and funding to address competing priorities. Besides the challenge of dealing with multiple competing priorities, community officials face another challenge: low risk awareness of hazards by the public and other stakeholders. In this paper, we discuss the potential of using virtual reality (VR) animations of natural hazards to enhance stakeholders' (e.g., the public, local/state/federal governments, insurance agencies, and property owners) risk awareness. By increasing risk awareness, VR animations of natural hazards and disasters could increase protective actions and enhance the community's hazard resilience (Mitchell, 1997).

2 Grand Challenges of Natural Hazards and the Role of Virtual Reality

Natural disasters not only result in substantial expenses for governments, businesses, and homeowners but also claim residents' lives. In 2017, Hurricanes Harvey, Maria, and Irma created a record level of damage that cost US$265 billion (Smith, 2018). On average, natural disasters kill about 60,000 people annually worldwide (Ritchie & Roser, 2014). Recent extreme weather events striking the United States and the world have become more frequent and more severe, which suggests that future impacts of climate change will further increase in severity. To mitigate these threats and increase communities' resilience, we need to increase risk awareness and understand communities' vulnerability to natural hazards so that we can take proactive measures. Hence, we need to educate stakeholders (e.g., governments, property owners, and the general public) about near-term and long-term plans for mitigation and adaptation to climate change.

Natural disasters impact impoverished regions more severely than more affluent regions. They kill more people in low-to-middle income countries than high-income countries as the former lack the necessary infrastructure to withstand and respond to hazards (Ritchie & Roser, 2014). For example, stronger physical civil structures and infrastructures can withstand more intense storms, which leads to less damage and, thus, less property loss. Furthermore, better communication and messaging systems can provide timely information of inclement weather to the public, which allows people to take protective actions. Thus, communities need to strengthen their physical, civil, and social infrastructures against potential damage due to natural hazards to build resilience.

In addition to the challenge associated with enhancing physical and social infrastructures, other challenges to achieve community resilience to natural hazards revolve around a common theme: the lack of risk awareness or protective actions due to the following reasons (Jackman & Beruvides, 2013):

1) Stakeholders may experience fatigue or lose interest in proceeding with plans after the mitigation-planning process.
2) When a significant disaster has not occurred recently, stakeholders may perceive that no disaster will ever happen.
3) Compared with more frequent and familiar problems, natural disasters' complexity and infrequent nature place resilience to natural hazards low on planners' list of priorities.

Low risk awareness can hinder stakeholders from improving physical and social infrastructures. Therefore, we need to enhance community leaders', planners', and citizens' risk awareness and understanding of climate change-induced natural hazards. Changing risk awareness and understanding can help increase behavioral intentions to take proactive measures, which include building beyond property owners' code protocols or reinforcing one's property beyond the building code protocols that law requires, installing safe rooms in properties, and/or building more public storm shelters at designated sites. One way to enhance risk awareness and understanding of the consequences of natural hazards involves using VR to visualize the impact and potential damage that these hazards can cause. One can also use VR to guide and assist stakeholders in making decisions about natural hazards by visualizing the effects that actions to protect against them may have (e.g., how they can save lives and reduce costs). Taking appropriate protective actions to mitigate the effects of these hazards develops community resilience.

In this paper, we propose developing VR animations of tornado hazards to increase community officials' and property owners' risk awareness of tornado disasters. We formed an interdisciplinary team to capitalize on the knowledge of different disciplines (Zhang, Nah, & Preece, 2004) to develop realistic and credible VR. A computer scientist with numerical mathematics background and a civil engineering scientist with extensive research experience in tornado modeling will lead the VR development effort. A human-computer interaction scientist with a background in computing, information systems, and psychology plans to conduct usability evaluations throughout the development process. A psychologist will oversee the experiments on and measurement of perceptions. To help implement the VR animations, this interdisciplinary research team plans to actively engage community decision makers and stakeholders to understand their community resilience goals and priorities and the city capacity for implementing protective actions to help determine the hazard intensities that the team will simulate in VR. Considering the critical role of the National Weather Service (NWS) in disseminating information about natural hazards, the NWS will offer guidance on the development and evaluation of the VR animations and help facilitate outreach to the community.

In our preliminary work, we use computational fluid dynamics and computational structural dynamics to model and visualize the dynamics of tornado hazards and how civil structures respond to them (Honerkamp, Yan, & Snyder, 2020; Li, Yan, Yuan, & Chen, 2019; Li, Honerkamp, Yan, & Feng, 2020). Based on these structural responses, we are developing VR animations of the effects that the hazards have on civil structures to help stakeholders understand the hazards' consequences and how well protective actions increase community and property resilience. We need more research to create and enhance awareness and understanding of hazard mitigation efforts, which can help minimize damage and casualties due to natural hazards.

3 Virtual Reality for Creating Risk Awareness and Understanding of Natural Hazards

VR refers to "a computer-generated simulation of a lifelike environment that can be interacted with in a seemingly real or physical way by a person, esp. by means of responsive hardware such as a visor with screen or gloves with sensors" ("Virtual reality", n.d.). VR uses headsets (i.e., a head mounted display), controllers, and high-resolution devices to display virtual or imaginary environments for interaction through using sensory stimuli that include realistic visual displays and sounds (Steuer, 1992).

A VR system comprises five features (Wickens, 1992):

1) 3D (perspective and/or stereoscopic) viewing
2) Dynamic (vs. static) display
3) Closed-loop (interactive or learner-centered) interaction
4) Inside-out or viewer's frame of reference (i.e., ego-referenced as compared to world-referenced or outside-in)
5) An enhanced sensory experience

Hence, a VR user will experience a dynamic 3D display of a simulated environment with the capability to not only actively navigate in and interact with the environment but also receive enhanced feedback through multiple sensory modalities. VR's key elements and strengths include immersion, presence, and interactivity (Stephanidis et al., 2019). Immersion refers to the sense of being surrounded or enveloped by the simulated environment, and presence refers to the perception of being situated in the environment (Witmer & Singer, 1998). Interactivity refers to the ability to modify a mediated environment's form and content in real time (Steuer, 1992). Extending from virtual worlds into an immersive 3D environment, VR experience facilitates learning by creating a sense of immersion and realness of being present in a simulated environment

(Eschenbrenner, Nah, & Siau, 2008; Nah, Eschenbrenner, & DeWester, 2010, 2011; Ryan, 2001; Siau, Nah, Mennecke, & Schiller, 2010; Suh & Lee, 2005) that one can use to visualize natural hazards' impact and consequences. A key challenge that one faces when using VR is to create a hazard experience that people find credible and real (Hou, Nah, Yan, Stone, & Sabharwal, 2020; Mitchell, 1997).

One can use VR to educate and inform stakeholders about natural hazards and their associated risks and, thus, to increase their risk awareness and management of such hazards. Researchers have used VR to increase learning engagement and achievement in science (Liu, Wang, Lei, Wang, & Ren, 2020). In comparing three types of VR-based engineering education systems (i.e., Corner Cave System and head mounted display with and without a tracking system) with a no-VR control group, Alhalabi (2016) found that the VR groups achieved higher quiz scores than the control group. VR improved perceived learning and satisfaction with learning by increasing presence, motivation, active learning, reflective thinking, and enjoyment (Lee, Wong, & Fung, 2010; Makransky & Lilleholt, 2018; Suh & Lee, 2005). VR could increase arousal and risk perceptions of hazards by creating fear (Chittaro, Sioni, Crescentini, & Fabbro, 2017). A VR that simulated human distress and high emotions during a fire increased users' anxiety, risk assessment, and attitudes toward fire safety (Chittaro & Zangrando, 2010). In Table 1, we provide examples to illustrate how researchers have used VR to help increase stakeholders' risk awareness of natural hazards and manage the risk they pose.

VR can render a hazard's dynamics to create a realistic 3D simulated experience that can help stakeholders learn about the hazard, understand the risks associated with it, and plan to implement protective actions (e.g., proper rescue, escape, or evacuation procedures). For example, researchers in Japan developed a simple VR simulation of tornado hazards to increase tornado risk awareness (Mitsuhara & Shishibori, 2020). Researchers have also used VR to simulate fire hazards to provide trainees with a realistic fire scenario where they can learn about fire safety by extinguishing fire or assessing the safety of different paths to determine the safest path for evacuation or rescue (Çakiroğlu & Gökoğlu, 2019; Cao et al., 2019; Cha et al., 2012; Saghafian et al., 2020; Smith & Ericson, 2009; Tepe et al., 2018; Xu et al., 2014). Elsewhere, researchers used a VR simulation of fire spreads and extinguishment support to provide firefighters with feedback on their actions in applying extinguishing agents during training (Moreno et al., 2014). In addition, using VR creates better communication of flood hazard risks while helping to raise the community's attention about flood hazards and hazard preparedness, thus facilitating emergency planning (e.g., evacuation routes and assembly points) (Erikson et al., 2018; Macchione et al., 2019). Similarly, researchers have used VR to offer earthquake emergency training and drills to enhance earthquake preparedness and evacuee safety (Feng et al., 2020; Gong et al., 2018; Lovreglio et al., 2018; Sukiman et al., 2019). Based on a neural network-based VR, one can support decisions that involve managing resources and establishing work directions to restore cities that earthquakes have devastated by identifying dangerous and safe regions (Garcia et al., 2020).

Researchers have also applied VR to assess the vulnerability and enhance the sustainability of critical infrastructure. For instance, they have used VR to help stakeholders in Bulgaria tangibly understand the vulnerabilities that the country's electricity networks face from natural hazards and to facilitate decision making on managing risk and protecting electricity networks from natural hazards (Velev & Zlateva, 2018). Vulnerability analysis enables individuals to understand how susceptible a physical infrastructure is to disruption during a natural hazard (Velev & Zlateva, 2018).

4 Potential of Virtual Reality to Change Stakeholders' Hazard Perceptions and Hazard Mitigation Behavior

To increase the likelihood that individuals and other stakeholders will take appropriate protective actions to mitigate natural hazards' negative consequences, they need a better understanding about the hazards (see Section 3) and what protective actions are effective by personalizing the potential hazard risks. In turn, individuals develop a responsibility for protective action and community bondedness. As we explain in Section 3, one can use VR to enhance learning and risk awareness. VR can also help to change attitudes and behaviors.

Table 1. Examples of VR Simulations of Natural Disasters to Increase Risk Awareness

Reference	VR application	Implications
Çakiroğlu & Gökoğlu (2019)	VR-based fire safety behavioral skills training	Enhance basic behavioral skills for fire safety
Cao, Lin, & Li, (2019)	VR-based simulation of fire in evacuation	Understand the influence of spatial exploration mode on wayfinding performance during fire emergency
Cha, Han, Lee, & Choi (2012)	VR-based fire training simulator	Facilitate training and evaluation on fire hazard risk assessment
Chittaro & Zangrando (2010)	VR simulation of damaging effects of smoke due to fire	Create awareness of personal fire safety and change attitudes toward smoke in evacuating buildings
Erikson et al. (2018)	VR-based flood simulation	Estimate coastal flood hazards and vulnerabilities, and convey flood hazard risks
Feng et al. (2020)	Customizable VR simulation for earthquake emergency training	Enhance immediate response to earthquakes and post-earthquake evacuation
Garcia, Trejo, & García (2020)	Neural network-based VR for reconstruction of devastated cities by earthquakes	Facilitate intelligent management of resources and establishment of work directions to restore cities to normalcy
Gong et al. (2015)	VR-based education system for earthquake drills	Enhance public awareness of earthquakes and mitigate damage through preparedness using drills
Lovreglio et al. (2018)	VR prototype to train building occupants to cope with earthquake emergencies	Enhance evacuee safety and earthquake preparedness
Macchione, Costabile, Costanzo, & De Santis (2019)	VR-based flood simulation	Facilitate flood risk communications and emergency planning and preparation
Mitsuhara & Shishibori (2020)	VR simulation of tornadoes	Enhance risk awareness, fear, and learning motivation to cope with tornadoes
Moreno, Posada, Segura, Arbelaiz, & García-Alonso (2014)	VR simulation of fire spreads and extinguishment support	Enhance training in fire extinguishment
Saghafian, Laumann, Akhtar, & Skogstad (2020)	VR simulation for fire extinguisher training	Enhance fire safety through extinguisher training
Smith & Ericson (2009)	VR simulation of fire to teach fire safety	Enhance learning about fire hazards and practice escape techniques
Sukirman, Wibisono, & Sujalwo (2019)	Mobile VR simulation of earthquakes	Enhance earthquake preparedness and evacuation
Tepe, Kaleci, & Tuzun (2018)	VR-based fire drills	Enhance learning about fire safety
Velev & Zlateva (2018)	VR-based simulation on vulnerability of electricity networks from natural hazards	Facilitate decision-making on risk management, protection, and maintenance of national critical infrastructure
Xu, Lu, Guan, Chen, & Ren (2014)	VR-based fire training simulator with smoke hazard assessment capacity	Facilitate fire hazard risk assessment to identify the safest path for evacuation and rescue

According to the protective action decision model (PADM), past experience with hazardous events (e.g., earthquake, flood, and hurricane) relates strongly to individuals taking protective actions (e.g., heeding warnings, reinforcing homes against natural disasters) against such events in the future (Lindell & Perry, 2012). For example, with regard to the violent tornadoes that struck both Tuscaloosa, Alabama, and Joplin, Missouri, in 2011, a telephone survey found that, among people who received tornado warnings, the percentage of people in Tuscaloosa who took protective action (e.g., took shelter or tried to evacuate from warned tornado paths) did not differ by the number of sources of warnings received, whereas the percentage of people in Joplin who took protective action increased with the number of sources of warnings received (Luo, Cong, & Liang, 2015). Given that Tuscaloosa experienced more and stronger tornadoes than Joplin between 1995 and 2011, residents in Tuscaloosa were more likely to personalize the risk and take protective action after receiving the first warning. Hence, as warning information sources increased, the likelihood that people took protective action increased in Joplin but not in Tuscaloosa. Similarly, individuals with more experience with hurricanes rated hurricanes as having higher risk (Rickard et al., 2017). Besides past experience, knowing if a protective action will actually be effective (i.e., protective action efficacy) is often strongly related to protective action (Terpstra & Lindell, 2013). As for fire hazards, people's perceived consequences of these hazards best predicted their perceived risk (Champ & Brenkert, 2016). Being able to personalize losses (i.e., consequences) based on direct experience constitutes another factor related to protective action (e.g., Lindell & Perry, 2000, 2012). Previous research has found that people have a higher likelihood to make seismic adjustments (i.e., protective actions) when they personalize earthquakes' consequences (Lindell & Perry, 2000), and people are more likely to follow protective action messages during a hazard if they find the messages personally relevant (Heath, Lee, Palenchar, & Lemon, 2018). That is, when a natural hazard poses a more salient damage risk, individuals have a higher likelihood of taking protective measures against it. Mitchell (1997) also emphasized using VR to provide people with direct experience with natural hazards, which constitutes a powerful mechanism to increase protective actions against hazards. Even though Mitchell (1997), citing Burton, Kates, and White (1993), noted that "since the response to a hazard is related to one's perception of it, the virtual experience can heighten perceived risk and lead individuals to seek mitigation methods" (p. 261), it does not appear that such applications existed at that time. Limitations in VR at the turn of the century and the lack of interdisciplinary research teams possibly deterred individuals from applying VR to hazard-mitigation issues.

Applying VR to study hazard mitigation allows one to directly test the PADM. Although the literature has indicated that individuals perceive greater hazard risks when they have not only more experience with the hazard but also higher efficacy of protective actions and greater personalization of the hazard's consequences (with or without protective action), these findings are correlational in the literature. We propose the need to directly test PADM to assess whether one can enhance individuals' risk perceptions by directly exposing them to VR animations of the hazards and their consequences, and whether VR animations can develop more accurate perceptions of protective action efficacy (i.e., higher ratings of protective action efficacy). In other words, we posit that VR animations of natural hazards have the potential to directly impact these factors and increase protective actions. In turn, individuals who better understand hazard risks and perceive higher protective action efficacy should enhance community bondedness and the degree to which they take responsibility for protective action (i.e., preparedness for hazards).

Individuals with more hazard exposure often perceive community resilience to be lower than individuals who have not been exposed to hazards (Houston, Spialek, First, Stevens, & First, 2017) probably due to having experienced community devastation; however, VR animations have the potential to demonstrate protective action efficacy and personalized hazard consequences to increase community bondedness and protective actions (Lindell & Perry, 2000). Even with community bondedness (the sense that "we are in this together"), the question turns to who has responsibility for taking protective actions. When considering built structures, such as businesses or housing, organizational leaders generally have responsibility for the buildings they own (Sadiq & Graham, 2016) and homeowners tend to take more responsibility over their homes than the individuals who rent them (Mulilis, Duval, & Bovalino, 2000). We propose using VR to enhance individuals' sense of responsibility and community bondedness whereby all individuals take responsibility for protective actions that lead to community resilience. Just as gaming can enhance active learning (Haberyan, 2007) and increase confidence in learning (Stansbury & Earnest, 2017), VR animations could help individuals become immersed in hazardous events that reflect various protective actions' (e.g., reinforcing one's property) personal consequences. VR animations can help people understand natural hazards and efficacious protective actions to increase community bondedness and a sense of protective action responsibility, both of which relate to appropriate and timely protective actions against natural hazards. In our proposed tornado research, we plan to assess whether VR animations can personalize the hazard experience and enhance the implementation of protective actions, creating greater community resilience.

5 Conclusions and Future Research Directions

We urgently need to increase the extent to which individuals understand natural hazards and their associated risks. In line with Mitchell's (1997) call for researchers to use VR to help individuals experience hazards and motivate them to mitigate their risks, we are taking an interdisciplinary collaboration effort to develop and use VR to educate the public about natural hazards and to enhance hazard risk awareness. One can use VR to increase stakeholders' exposure to natural hazards and their personalized consequences (i.e., without protective action) and to demonstrate protective action efficacy (i.e., with protective action).

VR offers a promising medium to help stakeholders better understand natural hazards, their potential risks, efficacious protective action, and the proactive measures that can mitigate their negative consequences. In particular, we need research that directly tests the factors in PADM and the impact that personalizing the hazard experience has on the decision of taking protective actions. To personalize a realistic and credible VR experience to stakeholders, one should develop VR based on physical data through related meteorological and engineering simulations, which require close collaborations among computer science, meteorology, and different engineering fields. By applying machine learning and/or artificial intelligence, one can automatically collect historical data of previous disasters, which can enhance the database of the physical data to produce a more interactive and vivid VR. We also need additional research to explore the possibility of developing VR applications that a diverse population, which includes socially vulnerable populations (e.g., people with low income, people with disabilities, elderly, and the homeless), can access. That is, researchers need to make the VR environment easy and intuitive to use by applying human-centered design principles (Zhang & Venkatesh, 2018) and ensure they can easily scale it up or down and transport it to different cities and diverse settings. Researchers could offer various interaction modes, including hands-free gestures, such as head or body gestures (Prilla, Janßen, & Kunzendorff, 2019). Multi-modal VR animations can offer user experiences that specific hardware or software does not constrain and that can range from a leaner experience due to hardware and software constraints to a rich and highly immersive experience that offers the realism of a natural hazard. We will need additional research to investigate ways to make these tools cost effective and, most importantly, to demonstrate with cost-benefit analyses that these VR applications benefit stakeholders.

Although we focus on natural disasters in this paper, future research also should evaluate whether one can apply VR and augmented reality to educate individuals about other life-threatening situations, such as man-made disasters, active shooter situations, and pandemics. These situations resemble natural hazards in that they occur relatively infrequently but can have catastrophic consequences if people do not heed proper protective actions. People need to be able to personalize these VR applications and, as Mitchell (1997) forewarned, perceive them as real and believable, not as games or unlikely events, or people will not likely take them seriously.

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