Information Requirements for Virtual Environments to Study Human-Building Interactions during Active Shooter Incidents

Runhe Zhu,[1] Burcin Becerik-Gerber,[2] Gale Lucas,[3] Erroll Southers,[4] David V. Pynadath[5]

[1]Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, 3620 South Vermont Ave., Los Angeles, CA 90089-2531, United States; e-mail: runhezhu@usc.edu
[2]Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, 3620 South Vermont Ave., Los Angeles, CA 90089-2531, United States; e-mail: becerik@usc.edu
[3]USC Institute for Creative Technologies, 12015 Waterfront Drive, Playa Vista, CA 90094-2536, United States; e-mail: lucas@ict.usc.edu
[4]Sol Price School of Public Policy, University of Southern California, Lewis Hall 312, Los Angeles, CA 90089-0626, United States; e-mail: southers@price.usc.edu
[5]USC Institute for Creative Technologies, 12015 Waterfront Drive, Playa Vista, CA 90094-2536, United States; e-mail: pynadath@ict.usc.edu

ABSTRACT

Active shooter incidents present an increasing American homeland security threat to public safety and human life. Several municipal law enforcement agencies have released building design guidelines intended to offer increased resilience and resistance to potential attacks. However, these design recommendations mainly focus on terrorist attacks, prioritizing the enhancement of building security, whereas their impact on safety during active shooter incidents, and corresponding human-building interactions (HBIs) that influence the outcomes (response performance), remain unclear. To respond to this research gap, virtual reality, with its ability to manipulate environmental variables and scenarios while providing safe non-invasive environments, could be a promising method to conduct human-subject studies in the context of active shooter incidents. In this paper, we identify the requirements for developing virtual environments that represent active shooter incidents in buildings to study HBIs and their impacts on the response performance. Key components constituting virtual environments were considered and presented. These include: (1) what types of buildings should be modeled in virtual environments; (2) how to select protective building design recommendations for active shooter incidents and model them in virtual environments; (3) what types of adversary and crowd behavior should be modeled; and (4) what types of interactions among participants, buildings, adversaries and crowds should be included in virtual environments. Findings on the above key components were summarized to provide recommendations for future research directions.

INTRODUCTION

Numerous active shooter incidents, especially in the U.S., have repeatedly reminded us of the significant threat that these incidents pose to public safety. According to the Federal Bureau of Investigation, between 2000 and 2017, active shooter incidents resulted in 779 fatalities and

1,418 injuries in the U.S., of which around 30% of fatalities and 50% of injuries happened in 2016 and 2017 only (U.S. Department of Justice and Federal Bureau of Investigation 2017). Some of the most recent active shooter incidents in 2018, such as the Stoneman Douglas High School shooting, Santa Fe High School shooting and Thousand Oaks bar shooting, further evidenced the urgent necessity of taking appropriate measures to mitigate the potential negative impacts of these tragic incidents. To improve public safety and building security, one approach is to design protective measures to be implemented in buildings in order to improve preparedness and resilience in response to active shooter incidents. Along this line, several reference manuals, including *Primer to Design Safe School Projects in Case of Terrorist Attacks* (FEMA 2003a) and *Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks* (FEMA 2003b) by the Federal Emergency Management Agency (FEMA), have been published to provide building design recommendations. While these guidelines can provide valuable insights in reducing the impact of active shooter incidents, many of their proposed recommendations (e.g., limiting the number of building entries, staggering interior doors) are focused on physical security and protecting buildings from adversaries and the methods (e.g., explosives) attackers use. Moreover, these guidelines are primarily focused on terror attacks, which may not have the same characteristics as active shooter incidents. Moreover, how these recommended building design attributes influence occupant responses when active shooter incidents actually occur in buildings, to the best of our knowledge, have not been explored by prior studies.

Human behavior and building attributes are intercorrelated and human-building interactions (HBIs) collectively determine the outcome of building emergencies (Li et al. 2017). Many past building emergency incidents have demonstrated that inappropriate building design could result in disastrous outcomes (e.g., stampedes) during building emergencies (e.g., the Station Nightclub fire of 2003) (Grosshandler et al. 2005). Building occupant responses influenced by building design (e.g., herding towards the same exit while ignoring other available ones) could significantly endanger individuals and decrease building performance during emergencies as well (Aguirre et al. 2011). Therefore, to evaluate building attributes that are aimed at mitigating the threat of active shooter incidents, it is necessary to incorporate human behavior into consideration and investigate HBIs during active shooter incidents.

Many research methods, such as emergency drills, controlled laboratory experiments, post-event surveys and interviews, and modeling and simulation, have been used to study HBIs during emergencies to avoid exposing people to life-threatening situations. However, these methods bear several intrinsic limitations, such as scarcity and incompleteness of available behavioral data, failure to represent complex human behavior, and lack of ability to represent realistic building emergency situations (Zou et al. 2017). Virtual Reality (VR) technology, a real or simulated environment in which the perceiver experiences telepresence (Steuer 1992), has become a promising research tool in this area. VR has been used to evaluate the effects of various building attributes in emergencies, such as signage and corridor configurations (Vilar et al. 2014), elevators and stairs (Andrée et al. 2016). Compared with other methods, explorations with VR can provide safe and more realistic emergency scenarios and has the ability to control various environmental variables (Zou et al. 2017). Yet, VR applications to study HBIs in active shooter incidents, to the best of our knowledge, are fairly rare.

Yet, there are several questions that need to be answered before implementing VR-based investigations on HBIs during active shooter incidents. One of the first steps is to identify what information has to be represented in VR environments and how these information requirements should be visualized in order to provide a realistic environment and high ecological validity.

Therefore, the objective of this paper is to present and discuss the information requirements for developing the crucial elements of a virtual environment for the sake of investigating HBIs during active shooter incidents.

UNDERSTANDING HBIs DURING ACTIVE SHOOTER INCIDENTS USING VR

Several elements, namely building attributes, building types and layouts, shooting scenarios, and human interactions with the environment are considered to constitute the core of a virtual environment for studying HBIs during active shooter incidents. The reasons for the importance of these elements and their information requirements are presented in the following subsections.

Building attributes

To study HBIs during active shooter incidents, building attributes (e.g., signs, exits, stairs) are indispensable components as they are directly related to human behavior during emergencies (Kobes et al. 2010). However, a practical question is yet to be answered: how to select building attributes that are aimed at mitigating the threat of attacks and evaluate their effectiveness in terms of safety and security using virtual environments? To tackle this issue, the first step could be a review of the published guidelines to identify the most widely proposed protective measures. However, not all of the measures are related to HBIs or relevant to active shooter incidents or could be represented in virtual environments, thus further considerations are needed for the selection process. Table 1 categorizes the objectives of these measures along with corresponding examples. For example, the measure 'Avoid exposed structural elements' does not have direct interactions with human behavior; another measure 'Avoid using glass along primary egress routes or stairwells' are primarily to protect buildings from bombs and explosions (FEMA 2003b), but this recommended building attribute may also have side effect such as decreasing the level of visual access, which could inhibit people's wayfinding performance during emergencies (Kobes et al. 2010).

Table 1. Objectives and examples of protective measures against attacks on buildings

Objective of the Measure	Examples of Protective Measures
To reduce the probability of attacks	Install active vehicle crash barriers; Limit the number of doors used for normal entry/egress; Eliminate hiding places.
To minimize the influence of attacks on buildings	Install blast-resistant doors and windows; Avoid exposed structural elements; Avoid using glass along primary egress routes or stairwells.
To protect occupants and facilitate sheltering and evacuation behavior	Create shelter-in-place rooms or areas; Ensure that exterior doors into inhabited areas open outward.
To improve emergency management	Install a backup control center; Install an electronic security alarm system; Install a CCTV surveillance system.

To this end, the authors reviewed several major guidelines and categorized the proposed protective measures, along with the frequency of these measures being proposed and whether they influence human behavior as well as whether they could be represented in VR, as shown in Table 2.

Table 2. Summary of protective measures proposed by major guidelines.

Protective measures	FEMA-426	FEMA-427	FEMA-428	FEMA-452	Does it influence human behavior?	Can it be represented in VR?
Install barrier	2		2	2	Y	Y
Make doors open outward	1		1	1	Y	M
Limit the number of doors for normal access	1	1	1	1	Y	Y
Stagger interior doors and offset interior and exterior doors	1		1	1	Y	Y
Use blast-resistant doors	1		1	1	N	N
Install a backup control center	1		1	1	N	N
Protect HVAC systems	7	13	9	7	N	N
Install security lighting, illuminate building access points	2		2	2	Y	Y
Control access	3	5	3	3	Y	Y
Protect utility systems	2		2	2	N	N
Install public address/alarm	3	1	2	2	Y	Y
Eliminate hiding places	1		1	1	Y	Y
Install CCTV camera	1		1	1	N	N
Install call button	1		1	1	Y	M
Reinforce foyer walks structurally	1		1	1	N	N
Isolate unsecured areas from secured areas	4	6	4	4	Y	Y
Avoid exposed structural elements	2		2	2	N	N
Locate stairs remotely. Do not discharge stairs into lobbies, parking, or loading areas	1		1	1	Y	Y
Use shelter rooms	1	1	1	1	Y	Y
Protect walls	3	1	4	3	N	N
Minimize interior glazing near high-risk areas.	1	1	3	2	M	Y
Protect fire system	1		1	1	N	N
Limit nonstructural elements such as false ceilings and metal blinds on the interior.	1	3	1	1	N	N
Limit column spacing		1			Y	Y

(Numbers in the table represent the frequency of measures being proposed in the guidelines; Y: Yes; N: No; M: Maybe)

Building types and layouts

Apart from building attributes, building types and layouts are also essential when developing virtual environments. First, unlike natural hazards (e.g., earthquakes), active shooter incidents are target dependent, hence buildings in the same area can have different risk levels. Second, human behavior depends on the type of buildings (e.g., residential vs. office buildings) (Proulx and Pineau 1996) and building layouts (e.g., spatial connectivity) (Tan et al. 2015). Selection of building types could be based on records of past active shooter incidents. For example, among the active shooter incidents in the U.S. from 2000 to 2017, 42% happened in commercial environments and 20.8% happened in educational environments, followed by open space (14%) and governmental areas (10%) (U.S. Department of Justice and Federal Bureau of Investigation 2017). With respect to the selection of building layout, there are two approaches that have been proposed by prior studies (Chittaro and Ranon 2009). The first one is to define the building layout based on an existing building. The major advantage of this approach is that it provides the opportunity to assess whether occupants follow the suggested responses in the emergency management plans and evaluate how people's familiarity with the building impacts their behavior (Lovreglio et al. 2017). Another approach is to use a hypothetical building. This approach is time-efficient since it does not require collecting any data on an existing building (Chittaro and Ranon 2009).

Nevertheless, to effectively investigate HBIs during active shooter incidents and generalize the research findings, an alternative approach needs to be developed due to the reasons elaborated here. First, functions of building attributes are dependent on the building layout. The effect of some building attributes (e.g., door size) can vary during emergencies as the complexity of building layout changes (Ha and Lykotrafitis 2012). Second, people's behavior during building emergencies is contingent upon the type, function and configuration of buildings (Kobes et al. 2010). For example, during the November 2015 Paris attack, a video recorded in a café showed that people who hid behind the bar were successful in not being found by the attacker (Li et al. 2017). Another example is office buildings, for which the two common layouts are open spaces and private offices. These layouts influence human behavior during active shooter incidents. For example, private offices could provide more cover and concealment opportunities for the occupants, whereas compared with open spaces, private office layout allows less social interactions (e.g., helping and competing behavior), which may influence people's responses during active shooter incidents (Li et al. 2017).

Therefore, to generalize research findings on HBIs during active shooter incidents, selected building layouts for the development of virtual environments should be representative. While for certain types of buildings (e.g., schools), the building layout can be geographically different by nature, the selection of building layout should still capture the characteristics of a building type in a certain region. To achieve this purpose, practitioners in related areas and industry standards could be referred to.

Shooting scenarios

Apart from building attributes, the shooting scenario is also a key component when developing virtual environments, as people's behavior can vary greatly in different attack scenarios. Compared with other emergencies (e.g., fires, earthquakes), active shooter incidents have several distinct characteristics. First, human adversaries are present in active shooter incidents. These adversaries are usually targeted at taking lives, which is very different from natural hazards (e.g., fires) and other types of terrorist attacks due to different weapons (e.g., firearms vs. bombs) the adversaries use. Moreover, adversaries can strategically respond to people's behavior and protective measures, while natural hazards (e.g., fires and earthquakes) follow certain intrinsic rules of evolution. Among 160 active shooter incidents in the U.S. between 2000 and 2013, all but two involved single shooters and most of them are males. In at least nine incidents, the shooter first shot and killed a family member(s) in a residence before moving to a more public location to continue shooting. In 40% of the incidents, shooters committed suicide, mostly at the scene of crime (Blair and Schweit 2013). Second, while building fires can last for hours and earthquakes have three seismic stages (Lovreglio et al. 2017), the duration of active shooter incidents is usually short: 69.8% of incidents ended in 5 minutes or less, of which the majority ended before police arrived (Blair and Schweit 2013). Third, crowd behavior during active shooter incidents are different from other emergencies. For example, in building fires, people usually evacuate the building quickly to escape from the fire and recommended actions during earthquakes are 'drop, cover, hold' (Lovreglio et al. 2017). Quite the contrary, in active shooter incidents, people are suggested to take 'run, hide, fight' actions.

Therefore, with respect to representing active shooter incidents in virtual environments, both the shooter(s) and crowds need to be taken into consideration. Shooter behavior could be modeled based on the review of past incidents. Nevertheless, it is not essential to model shooter behavior that perfectly captures real-world situations, as long as it can provide people with realistic experiences. That is, the simulated shooter(s) should pursue a plausible goal drawn from the behaviors of real-world shooters, while the specific details of how the shooter(s) pursues the goal is less critical. Alternatively, since the main objective is the investigation of HBIs, if needed, shooting scenarios could be represented by sounds of gunshots, people's screaming, or public announcement, instead of the presence of shooters. As for crowd behavior, while there is a lack of comprehensive knowledge of human behavior during active shooter incidents, some qualitative findings on human behavior during emergencies could be used. For example, it has been found that people tend to behave rationally instead of panicking, and pro-social behavior (e.g., helping behavior) is common during building emergencies (Kobes et al. 2010). For example, two possible shooting scenarios could be as follows:

1. In an office building, occupants in the office space hear the sound of gunshots from the cafeteria area of the building. Therefore, they start to evacuate orderly to shelter rooms through different evacuation routes (e.g., elevators vs. stairs).
2. In an academic building, a shooter walks in the hallway seeking targets. Students support each other, and some students choose to hide inside classrooms while some choose to run to different exits of the building to evacuate.

Human interactions with the environment

To effectively investigate HBIs during active shooter incidents, incorporating interactions between human subjects and virtual environments is indispensable. In terms of HBIs, human subjects' basic actions (e.g., navigating in the building) and basic information about the building (e.g., location and materials) that could be perceived by human subjects should be incorporated realistically. Moreover, other HBIs, such as opening/locking doors, could be carefully considered based on the target building attributes to be evaluated in the virtual environment. Likewise, incorporation of interactions between human subjects and virtual crowds could also be determined based on targeted building attributes due to several reasons, for example, the effect of some building characteristics (e.g., visibility level) could be evaluated based on human subjects' individual behavior (e.g., route choice) while other building characteristics (e.g., door size) can only be evaluated based on the crowd size and behavior, which necessitates interactions between human subjects and virtual crowds (e.g., pushing behavior). Furthermore, interactions between human subjects and shooter(s) depend on the modeling of shooter behavior. To make the virtual environment more realistic, indirect interactions (e.g., human subjects trying to hide while shooter(s) seek them) between human subjects and shooter(s) could be included. However, if the main focus is HBIs, direct interactions (e.g., fighting) between human subjects and shooter(s) may not be necessary.

DISCUSSION AND CONCLUSION

The use of VR experiments to study HBIs is a novel approach. This study presents a discussion about the requirements of developing virtual environments to evaluate building attributes that are aimed at reducing attack risk by investigating human-building interactions during active shooter incidents. Four crucial elements of VR, including building attributes, building types and layouts, shooting scenarios, and interactions between human subjects and virtual environments are discussed. We present an initial work on the requirements for developing virtual environments, however the complexity of HBIs requires a wider scope. First, in the selection of building attributes, individuals with differing roles and expertise (e.g., security personnel, facility managers, building designers) may have distinct opinions about these protective measures. Therefore, based on the review of guidelines, focus group techniques, which have been used by prior studies to identify factors influencing people's route choices during building emergencies (Gershon et al. 2007), could be used to determine building attributes to be incorporated. People from related backgrounds, such as safety and security experts, building designers, engineers, and building owners, could be included in the focus groups to provide comprehensive viewpoints. Moreover, to generalize research findings, comprehensive review of building layouts and active shooter incidents is needed. Building layouts could be determined based on the review of industry guidelines and consultation with related organizations (e.g., Building Owners and Managers Association), and shooting scenarios could hinge on a variety of sources, including governmental-issued documents, media reports, and video footage of active shooter incidents.

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