VIRTUAL REALITY-BASED STUDIES OF HUMAN EMERGENCY BEHAVIOR IN BUILT ENVIRONMENTS: A SYSTEMATIC REVIEW

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ABSTRACT: *Human behavior is one of the most influencing factors of safety during emergencies. Having a robust understanding of human behavior can improve both emergency management practices and design strategies for built environments. Traditional methods to study human behavior include emergency drills, post-event surveys, controlled laboratory experiments, and emergency video analyses. However, these methods suffer from intrinsic limitations, such as scarcity of available data and lack of flexibility to quantify the impact of various factors (e.g., corridor width, number of exits) that might influence human behavior. With the recent advancements in virtual reality (VR) technologies, an increasing number of VR-based human behavior studies are seen in the literature. This study presents a systematic review of existing VR-based research on human behavior during emergencies in built environments. The review results demonstrate that fire emergencies and wayfinding behavior are widely studied while other emergency or behavior types are not well explored yet. The review results also suggest that many VR-based studies did not specify a target population or explore the impact of a particular type of built environment. In the light of the review findings, recommendations for future VR-based research on human emergency behavior in built environments are discussed.*

KEYWORDS: *virtual reality; human behavior; emergency; built environment; review.*

1. INTRODUCTION

Various natural and man-made disasters could occur in built environments, putting human safety in peril. For example, in 2016 only, 475,500 structure fires occurred in the United States, resulting in 2,950 civilian deaths and 12,775 civilian injuries (Haynes, 2017). Human behavior is one of the most decisive factor for human safety during emergencies. It was reported that in many emergency situations, most victims were killed or injured by the non-adaptive behavior of the crowd (e.g., pushing and trampling on each other), instead of by the actual cause of emergencies (Pan et al., 2006). One way to mitigate the risk of emergencies in built environments is to use a "behavioral design" approach by taking human factors into consideration for developing effective risk-reduction strategies, which requires comprehensive knowledge of human behavior during emergencies (Bernardini, D'Orazio, et al., 2016).

It is not a trivial task to understand human behavior during emergencies. Unlike in normal situations, people tend to behave differently in emergencies under high physiological and psychological stress (Ozel, 2001). Human emergency behavior is based on the perception of the situation, intention to act, and considerations involved before actions (Kobes, Helsloot, de Vries and Post, 2010). For example, people may not evacuate a building when they hear a fire alarm. Instead, they may first attempt to understand the situation, wait for more cues (e.g., smell of smoke, others leaving the building), and seek more situational information (Latane and Darley, 1968). Social behavior is also common during emergencies. When emergencies occur, people with strong social relationships (e.g., families and close friends) usually act as a group and may even take detours to search for missing members (Kobes, Helsloot, de Vries and Post, 2010). Moreover, it has been illustrated that many building attributes, such as visual access, architectural differentiation (i.e., unique building characteristics which people could use for orientation purposes), signage, and plan configuration, could impact people's evacuation performance in emergencies (Raubal and Egenhofer, 1998), which makes human behavior during emergencies more complex.

Due to legal and moral reasons, it is virtually impossible to expose people to life-threatening conditions to study their behavior during emergencies (Hancock and Weaver, 2005). In response, a variety of alternative approaches have been proposed. Emergency drills have been widely performed in emergency behavior studies (Kobes, Helsloot, de Vries, Post, et al., 2010). However, a major limitation of emergency drills is the lack of sense of presence, which may cause different evacuation behavior from real emergencies (Muir, 1996). Although unannounced drills could partially mitigate this limitation, it is still costly to conduct drills and difficult to control environmental variables (Haghani and Sarvi, 2017a). Additionally, post-event surveys and interviews have been widely used. However, bias may exist in participants' memory and responses, even if they have real emergency experiences (Kuligowski, 2016). Hence, the collected data may not accurately reflect their actual behavior during emergencies. Controlled laboratory experiments provide an alternative way to study human behavior during emergencies. Unlike emergency drills, controlled laboratory experiments normally take place in temporary physical setups in laboratories, which offers better environmental manipulation and field observation (Haghani and Sarvi, 2017a). However, controlled laboratory experiments may suffer from insufficient sense of presence experienced by participants, and whether the experiment results amount to reliable reflection of real-world scenarios remains uncertain in many cases. A variant way of conducting controlled laboratory experiments is using non-human subjects (e.g., mice and ants) and exposing them to real hazards. While this approach could avoid exposing human participants to hazardous situations, the behavioral similarities between humans and other animals are still debatable (Parisi et al., 2015). Alternatively, video records could be used to obtain behavioral data from past emergencies. The major advantage of this approach is that it is based on real behavior. However, it is limited by the scarcity and incompleteness of available data (Haghani and Sarvi, 2017a). Also, various simulation tools have been developed to model human responses during emergencies by setting predefined rules for human behavior. Nevertheless, human psychological responses and physical behavior are usually highly complex in emergencies and difficult to predict, while comprehensive behavioral theories to guide simulations are lacking (Kuligowski and Gwynne, 2010). As a result, it is very challenging for simulations to represent fine-grained human behavior in emergencies.

Apart from the above approaches, virtual reality (VR) has become a promising tool. VR generally refers to the technology used to generate computer-simulated environments that give a viewer a convincing illusion and a sense of being inside an artificial world in the computer (Castronovo et al., 2013). Compared with other approaches, VR-based behavioral experiments can provide safe and non-invasive environments, the flexibility to cover a wide range of topics, and the capability of retaining various control variables (Haghani and Sarvi, 2017a; Kinateder, Ronchi, Nilsson, et al., 2014). In recent years, VR applications in this research area have been exploited, whereas an understanding of the current status of this area is lacking. Moreover, with the rapid growth of VR technology, VR has increasing potential of being used to study human behavior during emergencies. Thus, it is necessary to shed light on future research directions by synthesizing prior studies. To address this gap, this study presents an in-depth review of VR-based research on human behavior during emergencies in built environments, identifies the latest accomplishments and limitations of current studies, and provides recommendations for future research.

The remainder of the paper is organized as follows: Section 2 describes the objectives and methodology of this review. Section 3 provides a comprehensive review of VR-based research on human behavior during emergencies in built environments. Discussions and recommendations for future research are presented in Section 4. Section 5 concludes the paper.

2. RESEARCH OBJECTIVES AND METHODOLOGY

The first objective of this study is to advance our understanding of the current achievements and limitations of VR-based research on human emergency behavior in built environments. The second objective of the study is to put forward recommendations, based on the synthesis of prior studies, for future research to promote the use of VR in studying human emergency behavior in built environments. To systematically present this research area, the literature was analyzed from 6 perspectives: (1) Since the main aim is to develop our understanding of human emergency behavior, what human behavior has been investigated in prior studies was described; (2) Different populations may have distinct behavioral patterns, due to their different lifestyles, abilities, and roles (Gerges et al., 2017). Thus, the target population of prior studies was analyzed; (3) It has been pointed out in prior research that human behavior may vary in different emergency scenarios (e.g., fires, earthquakes, flood, etc.) (Bernardini, Quagliarini, et al., 2016), thus the types of emergencies examined in prior studies were presented; (4) Built environments can have critical impacts on human behavior during emergencies (Kobes, Helsloot, de Vries and Post, 2010). Therefore, built environments and their attributes studied in prior studies were reported; (5) The attributes (e.g., display size, stereoscopy, head-tracking) of VR devices can impact the sense of presence experienced by participants (Castronovo et al., 2013). VR environments, including built environments and hazards mentioned in the last two points, and non-playable characters (NPCs) are also essential for implementing VR tools and experiments (Rüppel and Schatz, 2011). Thus, the VR systems (i.e., VR devices and NPCs) used in prior studies were reviewed and discussed; and (6) An essential concern of using VR to study human emergency behavior is the ecological validity – whether the experiment results can be repeated in real-world scenarios (Zou et al., 2017). In response, the validation methods used in prior studies were presented.

Driven by the above objectives, major electronic databases of scientific publications, including the "Web of Knowledge," "Scopus," and "Google Scholar," were used to search for the relevant articles. A combination of keywords, including "human behavio*", "emergency/disaster/extreme event/extreme environment", and "virtual reality/virtual environment/virtual experiment/immersive virtual environment/immersive virtual reality" were used in the search process. Since virtual environments refers to computer-simulated environments in this paper, the search was limited to 2000 and beyond. To gain a comprehensive view of the research area, (1) theoretical studies (e.g., studies that analyzed the feasibility of VR applications), (2) studies that developed VR tools that aimed at investigating human emergency behavior without conducting VR-based experiments, and (3) studies that involved VR experiments were all included in the review. Articles beyond this scope were excluded. Examples of excluded studies, which were manually filtered from the search results, included those that did not focus on human emergency behavior in built environments (e.g., aircraft emergencies), those that developed VR tools for emergency training purpose only, and those that did not use computer-simulated environments for the claimed virtual experiments (e.g., hypothetical-choice experiments). In addition, to complement the search results, the forward and backward snowballing method was applied (Wee and Banister, 2016), by examining the references of articles in the search results, to find more relevant papers that met the above inclusion criteria. Duplicate recordings of the same work were removed (some journal papers are based on earlier conference papers, where the contents are similar, thus only the journal versions were included in this review). After this search procedure, a total of 48 articles were included in the review.

Fig 1. illustrates all of the reviewed articles sorted by the publication year and article type (one article was released on arXiv.org in 2018, thus not included in Fig. 1). The set of articles sparsely distributed in a wide range of sources, including journals and conference proceedings, which demonstrated the highly interdisciplinary nature of the research area. The titles, in which most of the articles were published are: *Applied Ergonomics* (6), *Fire Safety Journal* (5), *Pedestrian and Evacuation Dynamics* (3), *Ergonomics* (3), *Computers in Human Behavior* (2), and *Journal of the Royal Society Interface* (2). Additionally, the publication year of the articles demonstrated that this research area has attracted an increasing attention in recent years.

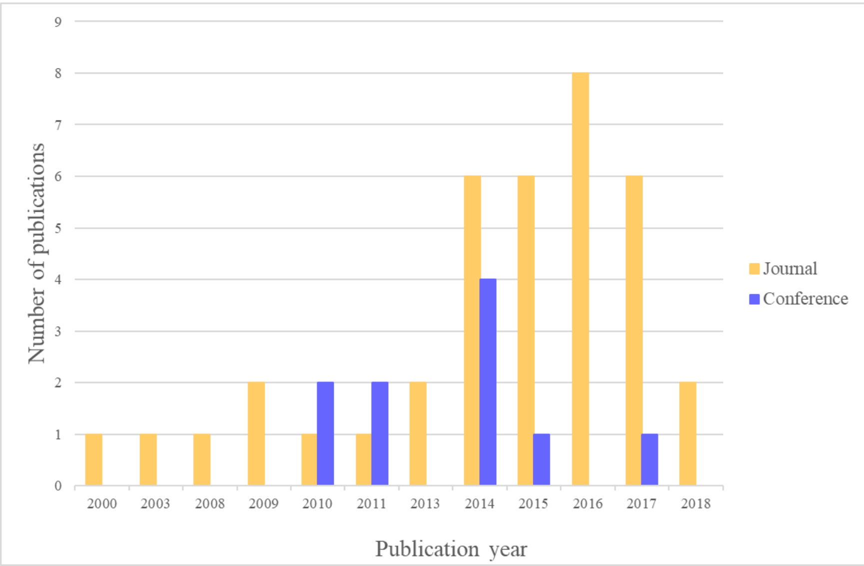

Fig. 1: Publication years and source types of the reviewed articles

3. REVIEW FINDINGS

3.1 Human behavior

Wayfinding and egress route choice are the most widely studied human behaviors in VR-based studies. The impact of building attributes on wayfinding during emergencies has been a popular topic. For instance, a hotel fire evacuation, conducted in both virtual and real-world experiments, demonstrated that the presence of exit signs could facilitate wayfinding during emergencies (Kobes, Helsloot, De Vries, et al., 2010). When smoke was perceptible, exit signs at the floor level was found to be more effective compared with signs at the ceiling level. In terms of corridor configurations, evacuees in a VR-based experiments tended to choose the corridor with more lighting at corridor intersections (Vilar et al., 2014). When both signage and different corridor configurations were present, evacuees' egress route choice was less likely to be influenced by the signage. Additionally, one VR-based experiment about the evacuation in a high-rise hotel showed that flashing green lights at the evacuation elevators could persuade evacuees to choose elevators (Andrée et al., 2016).

Furthermore, social interactions are crucial to the formation of human behavior during emergencies. Thus, social influence on wayfinding and egress route choice during emergencies has been examined in VR-based studies. Evacuees' egress route choice in tunnel fires under non-conflict (i.e., an NPC moving to the exit) and conflict (i.e., an NPC staying passive or moving to the opposite direction of the exit) social conditions were studied in VR-based experiments. The results demonstrated that evacuees were less likely to move to the exit in the conflict conditions compared with the non-conflict condition (Kinateder, Müller, et al., 2014). The combined effects of environmental and social factors on wayfinding and egress route choice during emergencies were also explored. The VR-based experiment in one study revealed that the presence of smoke, long distance of the exit, and high number of other evacuees near the exit reduced the probability of an exit to be chosen, while emergency lighting near the exit and flow of other evacuees through the exit had a positive effect (Lovreglio et al., 2016). Moreover, exit choice during emergencies was impacted by both the evacuees' familiarity of the built environment and other evacuees' choices. A VR-based experiment demonstrated that participants were more likely to exit through their familiar door, and this tendency was increased when the familiar door was chosen by other evacuees and decreased when the unfamiliar door was chosen (Kinateder et al., 2018). Compared with the social influence on wayfinding and egress route choice, social behavior amongst evacuees have been less studied in prior VR-based research. Drury et al. (2009) studied cooperative and competing behavior during emergency evacuations in an underground railway station. The VR-based experiment results illustrated that collective bonds might be strengthened and even created through the mutual experience of an emergency, and the amount of help that one would offer was affected by the level of danger. Gamberini et al. (2015) conducted a VR-based experiment in an office building in a fire emergency. The experiment demonstrated that light-skinned participants offered less amount of help to a dark-skinned NPC than to a light-skinned NPC, which indicated racial discrimination could occur during emergencies.

3.2 Target population

Target population refers to the population to which the findings of the studies are meant to generalize. In reviewed prior studies, only three specified their target population, while majority of the studies did not. One study targeted at light-skinned people to study racial discrimination in terms of the amount of help offered during emergencies (Gamberini et al., 2015). Another study investigated the influence of professional backgrounds on wayfinding performance in emergencies. Participants of the VR-based experiments from professional backgrounds (e.g., employees of construction companies, firefighters) did not show significant difference in their wayfinding performance (Tang et al., 2009). Moreover, a study focusing on helping and competing behavior during emergencies targeted at people with high or low sense of identification (i.e., whether they psychologically consider themselves as part of the crowd or not). The results demonstrated that those with high sense of identification were more concerned about others and offered more help (Drury et al., 2009). Apart from specific groups of population, demographic information (e.g., age and gender) was also collected in prior VR-based experiments. However, the information was used as control variables in most cases (i.e., balancing participants in different experiment groups) (Kinateder, Ronchi, Gromer, et al., 2014; Vilar et al., 2014). Only a few studies identified the impact of participants' demographics on their evacuation behavior. For example, male participants were found to have better wayfinding skills than female participants in building evacuations (Tang et al., 2009), and female and older participants appeared to have longer reaction times during virtual evacuations (Bode and Codling, 2013).

3.3 Emergency situations

With respect to the types of emergencies, the majority of prior studies (32 out of 48) were focused on fire emergencies. The prevalence of fire in the literature could be explained by three possible reasons. First, fire is one of the most frequent and disastrous types of emergencies in built environments (Haynes, 2017). Second, the study of human behavior in fires dates back to the 1950s, which provides theoretical support for the VR-based research (Fritz and Marks, 1954). Third, fire attributes, such as flames and smoke, can be modeled and visualized by particle systems embedded in many game engines (Rüppel and Schatz, 2011). 13 out of 48 studies did not specify their target emergencies. In these studies, hazards were not included in the virtual environment, and participants were only informed that there was an emergency, or an emergency alarm was played to them (Kinateder et al., 2018; Tang et al., 2009). The studies in this category mainly focused on the impact of emergency evacuation installations (e.g., signage systems) on human behavior (Tang et al., 2009), and evacuees' egress route choice during general building emergency egress (Bode and Codling, 2013). However, since hazards present in higher level of realism can provide more sense of presence experienced by participants (Zou et al., 2017), virtual environments without specified hazards may not elicit participants' sufficiently realistic emergency behavior. Terrorism related emergencies were only explored by one study. Chittaro & Sioni (2015) developed VR-based experiments that presented a terrorist attack in a train station. The virtual environment included smoke, metal debris and fire as the attack attributes. The experiment results showed that the interactive virtual environment could better enhance participants' risk perception and emotional response to the presented threat than the non-interactive version. Earthquake emergencies were only explored by two studies, in which VR-based experiments of a hospital experiencing an earthquake were prototyped (Lovreglio et al., 2018). The damaged environment was included in the virtual environment, and the shaking effect was simulated by setting up a vibrating platform on which the participants were seated.

3.4 Built environments

Built environments are critical in the formation of human behavior during emergencies (Bernardini, D'Orazio, et al., 2016). Fig. 2 illustrates the types of built environments and attributes of built environments considered by prior VR-based studies.

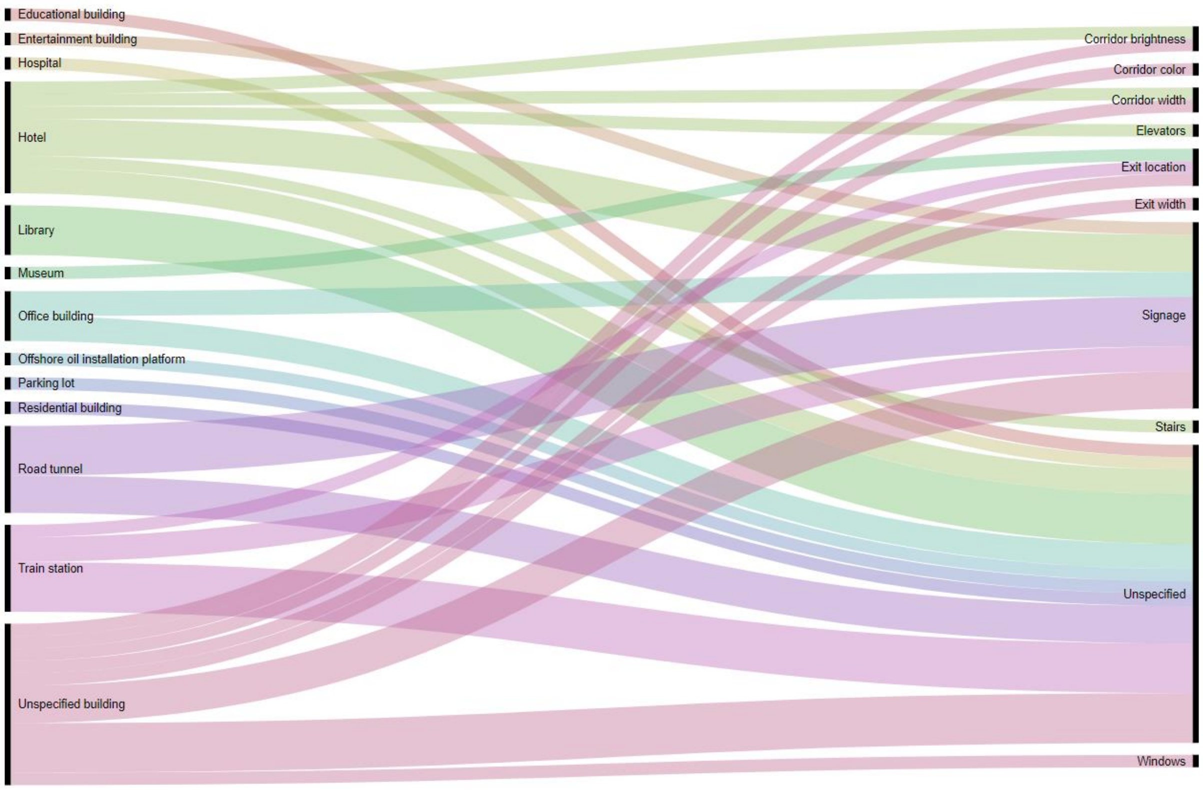

Fig. 2: Types and attributes of built environments considered in the reviewed articles

As shown in Fig. 2, Unspecified buildings are the most frequently studied type of built environments in prior VR-based research. In these studies, virtual environments were mainly based on buildings with no specified usage, or part of a building such as a room or a corridor (Bode and Codling, 2013; Vilar et al., 2014). Although a variety of built environments, including train stations (Drury et al., 2009), office buildings (Gamberini et al., 2015), hotels (Andrée et al., 2016), and so on, have been included in prior studies, the focus of these studies was mainly on human behavior exhibited during emergencies, while how these built environments impact human emergency behavior was not well explored. Among various attributes of built environments, signage, corridor and exit configurations have been most frequently studied. Other than these, one VR-based study investigated the impact of windows and corridor color on evacuees' route choice. The study reported that people tended to choose corridors with open windows and light color during evacuations (Abu-safieh, 2011). In another VR-based study, participants were asked to evacuate a high-rise hotel via stairs or elevators. It was found that participants generally waited either a limited time (less than 5 minutes) or a long time (more than 20 minutes) for elevators (Andrée et al., 2016). The possible reason for participants waited for a long time is that there was an announcement in the virtual environment, saying that the elevator could be used as an emergency exit.

3.5 VR systems

3D interactive desktop VR was the most widely used in the reviewed articles. When this technology is used, participants view 3D virtual environments through a monitor in front of them, and use controllers or keyboards and mice to navigate in the virtual environment (Drury et al., 2009; Tang et al., 2009). The main advantage of this method is that it is not demanding in terms of VR equipment, however, the level of immersion it can offer is limited (Nilsson and Kinateder, 2015). Head Mounted Display (HMD) was also commonly used. Participants' head orientation and movement can be tracked, and the virtual environment in participants' view can be updated accordingly in real time. HMDs can offer a feeling of immersion to participants, which makes it a promising tool for human emergency behavior studies (Nilsson and Kinateder, 2015). However, the usability of HMDs is still limited by technological challenges. For example, participants could not see their own body in many of the HMD systems (Nilsson and Kinateder, 2015). Cave Automatic Virtual Environment (CAVE) was another type of mainstream VR system used in prior studies. For the CAVE system, participants are placed in a room-sized cube and the virtual environment is projected on three to six (including the ceiling and floor) walls around the participant. In the environment, participants can use controllers or other interactive devices to navigate and interact with virtual objects, and their actions are tracked in real time (Nilsson and Kinateder, 2015). The main advantage of a CAVE system is the high immersion provided to participants, since participants can see their own body and are truly inside the virtual environment (Nilsson and Kinateder, 2015). However, compared with HMDs, CAVE systems are more cost-intensive and have higher requirements for space and computational power. Another VR technology is the powerwall. Virtual environments are presented stereoscopically on a powerwall screen, and participants can wear polarized glasses for 3D effects (Kinateder, Müller, et al., 2014). Apart from these methods, 2D interactive desktop VR was used only in two studies, in which participants could only see the virtual environment from a top-down view (e.g., (Bode and Codling, 2013)). Additionally, two studies used 3D non-interactive desktop VR, in which participants could only view pictures or videos of virtual emergency scenarios, without interacting with the virtual environment (e.g., (Lovreglio et al., 2016)). Furthermore, one studies conducted VR experiments with multi-participant enabled virtual environments, in which participants could virtually see and interact with each other (Moussaïd et al., 2016). However, the application of this system is highly subject to the available devices, such as the number of available HMDs and the graphics card performance (Lovreglio et al., 2017).

Including NPCs in the VR environment can provide the possibility to investigate the impact of other evacuees on evacuation behavior (Lovreglio et al., 2017). It also increases the sense of presence as in most cases, people evacuate with others. As shown in Fig. 3, many prior studies did not have NPCs in the VR environment. These studies mainly asked participants to perform tasks individually (e.g., wayfinding and exit choice) during the VR-based experiments and identified the impact of built environments on human behavior (e.g., the influence of signage systems on wayfinding) (Abu-safieh, 2011; Andrée et al., 2016). Crowds of NPCs were included in several studies. These studies mainly looked into how crowd movements induce stress and impact participants' egress route choice during emergencies (Bode and Codling, 2013; Lovreglio et al., 2016). Meanwhile, one NPC was used in VR-based experiments to examine the social influence on participants' egress route choice (Kinateder and Warren, 2016). Apart from evacuation behavior, other behaviors presented by NPCs, such as requesting help from participants, were incorporated in VR-based experiments as well (Gamberini et al., 2015). However, direct interactions between participants and NPCs are still lacking, which may limit the sense of presence experienced by participants (Nilsson and Kinateder, 2015).

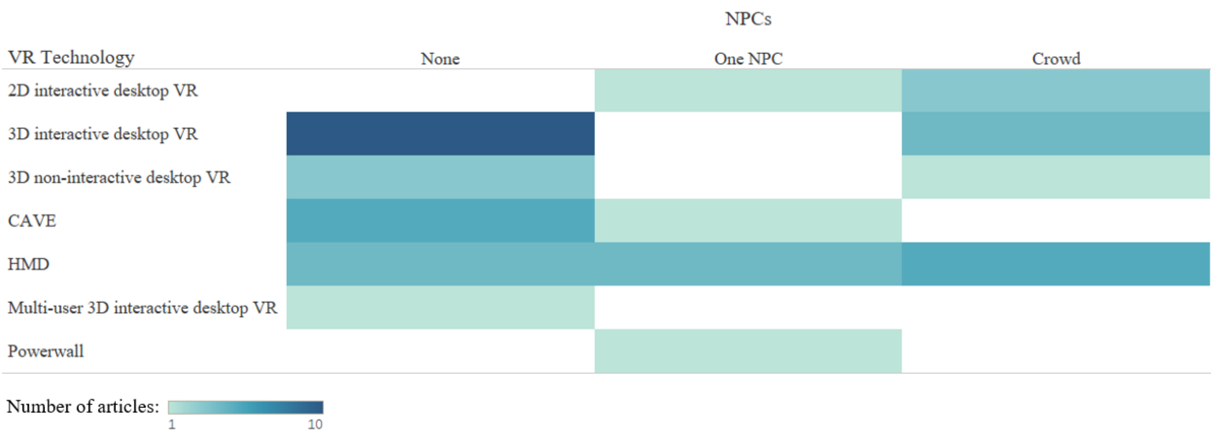

Fig. 3: VR systems and NPCs involved in the reviewed articles

3.6 Validation methods

Regarding the validation methods for VR-based experiments, 44% of prior studies used post-experiment surveys to measure ecological validity of the experiments. In these surveys, participants were often asked to evaluate their experience in virtual environments. Participants' anxiety, sense of presence, and simulator sickness during the experiments were often collected as an indicator of their feelings during the experiments (Kinateder, Ronchi, Gromer, et al., 2014; Zou et al., 2017). The possible reason for the wide use of surveys is that they are convenient to implement. However, survey data are based on participants' subjective responses, which may not always be a reliable indicator for ecological validity. Surprisingly, 31% of prior studies did not validate the virtual experiments, thus whether the experiment results could be transformed to real-world emergency scenarios was questionable. Physiological measurements were employed by 13% of prior studies. Skin conductance, heart rate, breath rate were commonly used in physiological measurements (Zou et al., 2017). The difference or ratio of physiological indicators before, during and after the experiment were analyzed to reflect the change of participants' feelings during the experiment. The physiological measurements generally showed that VR was capable of inducing emotional arousals, which was analogous to real-world emergency scenarios (Tucker et al., 2018). Comparison with real-world data is another validation method that can provide high credibility, which was used by 10% of prior studies. For example, one study compared moving trajectories in corridors in real and virtual environments and found the real-world data could be reproduced in the virtual environment reasonably well (Moussaïd et al., 2016). One difficulty in applying this method, however, is the lack of available real-world data. Additionally, one study considered participants' behavior in the virtual environment to measure the effectiveness of VR-based experiments. The study hypothesized that collisions between participants' virtual bodies and objects in the virtual environment, as well as participants' backward movement in the virtual environment would be more frequent during emergencies (Gamberini et al., 2015). To further validate the results of VR-based experiments, some of the above methods have been used in combination (e.g., questionnaires and physiological measurements) (Tucker et al., 2018; Zou et al., 2017). These psychological and physiological assessments showed that emergencies in the virtual environment could induce the emotional arousals experienced by participants.

4. DISCUSSIONS

Understanding human emergency behavior is the primary objective of this line of research. This review found that prior VR-based studies mainly explored participants' individual behaviors (e.g., wayfinding and egress route choice) and identified the impact of certain building attributes (e.g., signage systems and corridors) on human behavior (Tang et al., 2009; Vilar et al., 2014). Social influence has also been examined by prior studies, where the main focus has been the impact of crowd movements on people's egress route choice during emergencies (Bode and Codling, 2013). Although these investigations could provide valuable insights into human emergency behavior, the value of VR applications could be further advanced by more in-depth investigations of social interactions (e.g., helping and group-seeking) during emergencies. Moreover, people with different backgrounds may have distinct behavioral patterns, due to their different lifestyles, abilities, and roles (Gerges et al., 2017). For example, elderly people and people with disabilities were found to cause obstructions during evacuations because of their impaired mobility, thus special evacuation strategies need to be proposed for them (Gerges et al., 2017). By involving participants with different backgrounds in VR-based experiments, how human emergency behavior relates to their background (e.g., people's cultural background, daily roles, etc.) could be examined.

In addition, this review revealed that the types of emergencies studied in the literature are highly unbalanced. Human behavior during fires has been extensively studied, whereas other emergency situations (e.g., earthquakes and terrorist attacks) were much less investigated. Human behavior is subject to the impact of emergency situations, and some of the assumptions of human behavior (e.g., following crowd movement blindly during evacuation) may not always apply in all types of emergencies scenarios (Haghani and Sarvi, 2017b). Moreover, human behavior is also likely to vary significantly in different types of emergencies, such as earthquakes vs. fires (Bernardini, Quagliarini, et al., 2016). Thus, future VR-based research in this area could conduct experiments in different emergencies and examine how human behavior varies accordingly.

More importantly, human behavior and built environments are two interwoven elements in emergencies. Human emergency behavior is greatly influenced by built environments. Building layout, installations, size, etc. can all contribute to the formation of human behavior (Kobes, Helsloot, de Vries and Post, 2010). People's knowledge of built environments could also influence their egress route choice. It was observed that the familiar paths evacuees chose to go through might not be the shortest or safest ones (Kobes, Helsloot, de Vries and Post, 2010). In prior VR-based studies, only limited attributes (e.g., signage and corridors) of built environments were widely studied, while the impact of other attributes was less examined. Given that various attributes of built environments can be manipulated in virtual environments, future research could further study how built environments impact human behavior during emergencies. For example, the impact of attributes that belong to specific built environments (e.g., train platforms and ticket booths in train stations) could be explored.

Lastly, in terms of the ecological validity of VR experiments, it was repeatedly found that VR can be a valid tool to study human emergency behavior (Tucker et al., 2018; Zou et al., 2017). However, it is still difficult to achieve complete ecological validity. There remains technological challenges to promote VR applications in this area, such as limited multisensory (e.g., olfactory, haptic, and thermal) simulation, simulator sickness, and limited interactivity with the virtual environment (Nilsson and Kinateder, 2015). To address these issues, more advanced VR technologies (e.g., feedback gloves, omnidirectional treadmills) could be used in future research, and more appropriate validation studies would be valuable (Nilsson and Kinateder, 2015).

5. CONCLUSIONS

Human behavior is one of the most crucial determinants of human safety during emergencies in built environments. VR technologies, with the rapid developments in recent years, have been increasingly used to study human emergency behavior. Thus, the objective of this paper was to present a systematic review of VR-based studies on human emergency behavior in built environments and provide recommendations for future research. Six aspects of prior studies in this area, including human behavior, target population, emergency types, built environments, VR systems and validation methods, were analyzed to yield a holistic review of the state of the art. Wayfinding and egress route choice are the most widely studied types of human behavior during emergencies, while social behaviors (e.g., helping and group-seeking) among evacuees and how people's background (e.g., nationality, educational levels) influence their behavior have been less investigated. In terms of the types of emergencies, fires have been extensively explored, whereas other types of emergencies that can occur in built environments, such as earthquakes and terrorist attacks, received less focus. In addition, the impact of built environments on human emergency behavior was insufficiently examined in the literature, with only several individual attributes of built environments, such as corridors, signage ad exits having been investigated. Moreover, the interactions between participants and virtual environments including the NPCs included in these studies were limited in prior VR-based experiments. Future research could be done to further study human emergency behavior considering the interactions among humans, built environments and emergencies, and to increase the interactivity of VR-based experiments so as to further improve the validity of VR-based research in this area.

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